Emergent “light” and the high temperature superconductors

Pennsylvania State University
State College, January 21, 2016

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

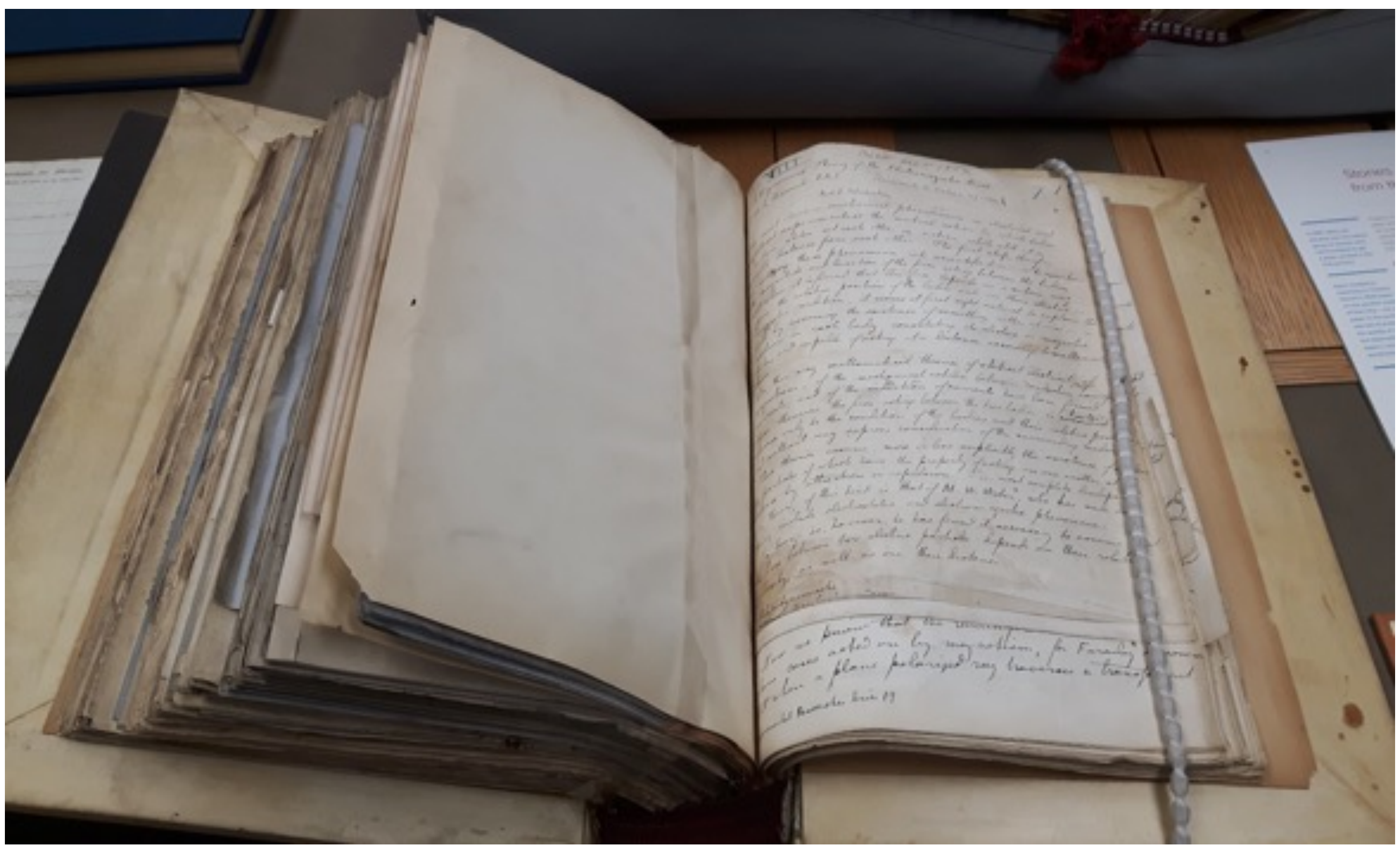
PHYSICS HARVARD

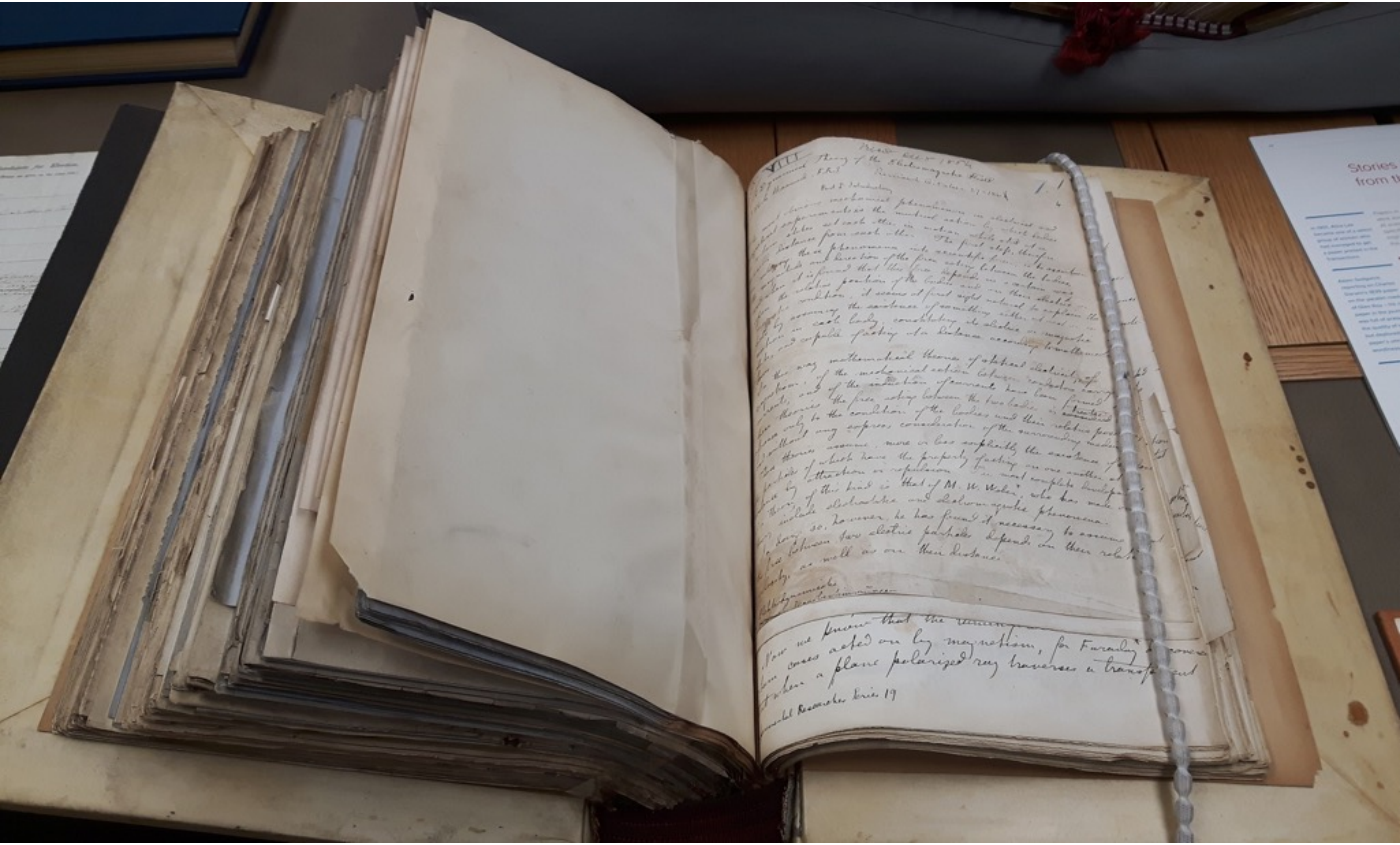
Maxwell's equations: 150 years of light

A century and a half ago, James Clerk Maxwell submitted a long paper to the Royal Society containing his famous equations. Inspired by Michael Faraday's experiments and insights, the equations unified electricity, magnetism and optics. Their far-reaching consequences for our civilisation, and our universe, are still being explored

Jon Butterworth

Sunday 22 November 2015 08.38 GMT, The Guardian





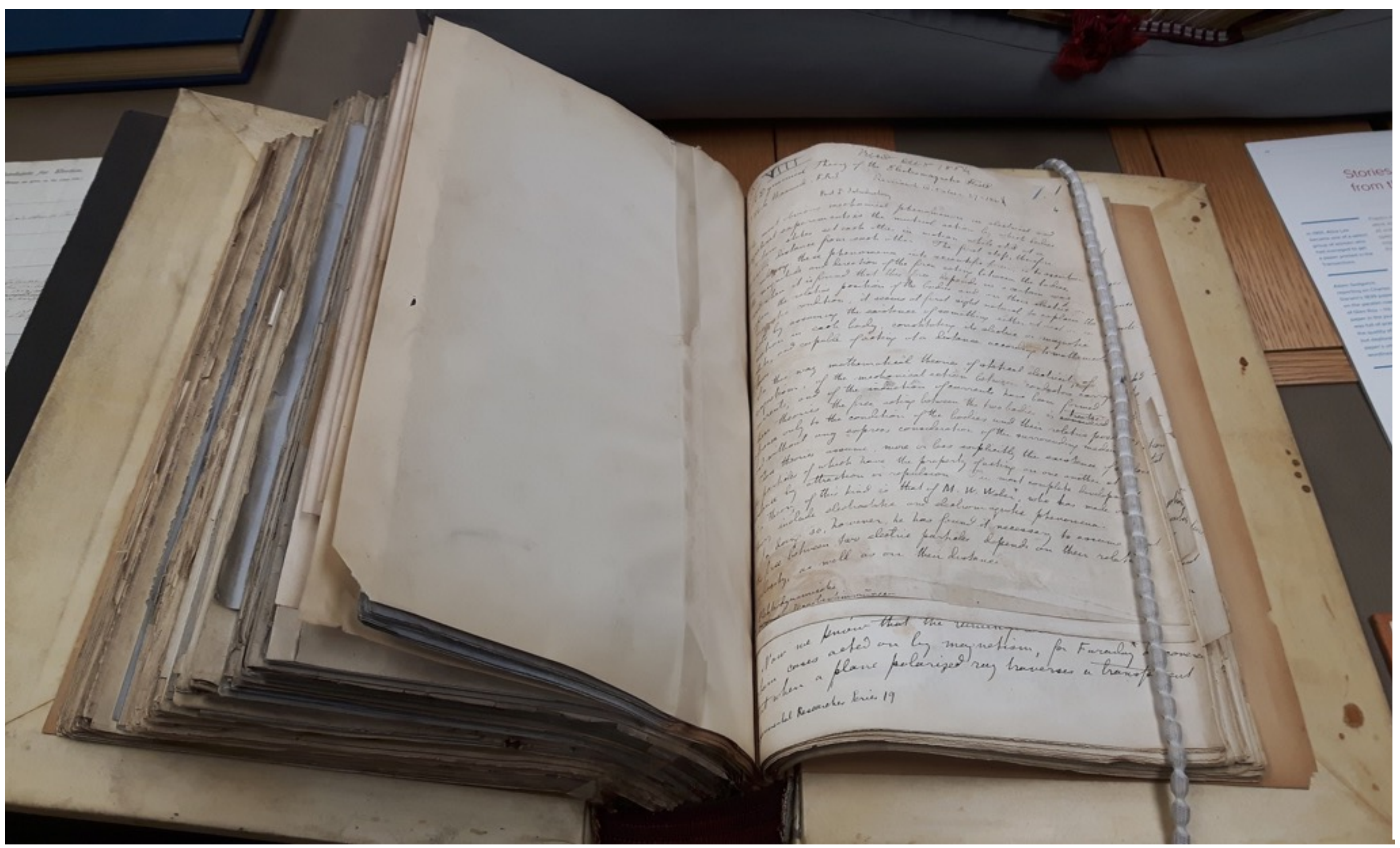
Now we know that the
cases acted on by magnetism, for Faraday
when a plane polarised ray traverses a transparent
Researches Series 19

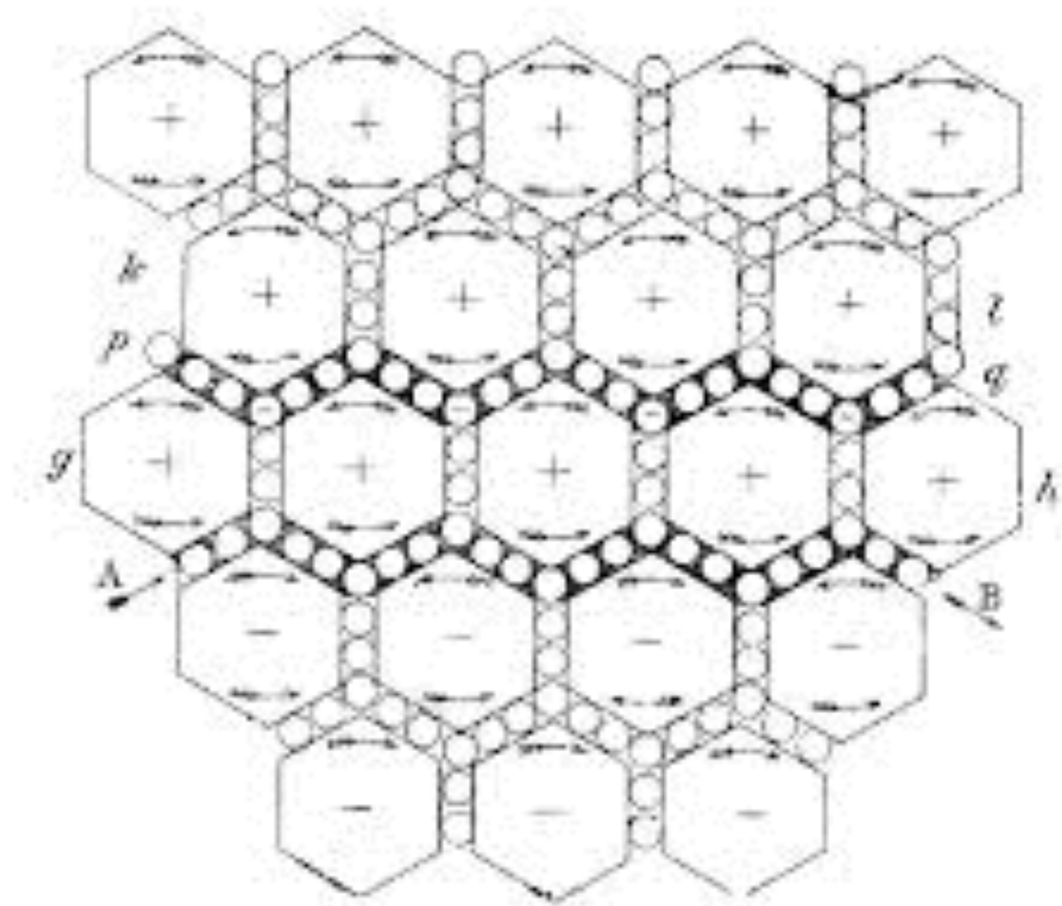
Maxwell's equations: 150 years of light

A century and a half ago, James Clerk Maxwell submitted a long paper to the Royal Society containing his famous equations. Inspired by Michael Faraday's experiments and insights, the equations unified electricity, magnetism and optics. Their far-reaching consequences for our civilisation, and our universe, are still being explored

Jon Butterworth

Sunday 22 November 2015 08.38 GMT, The Guardian





Modern point-of-view:

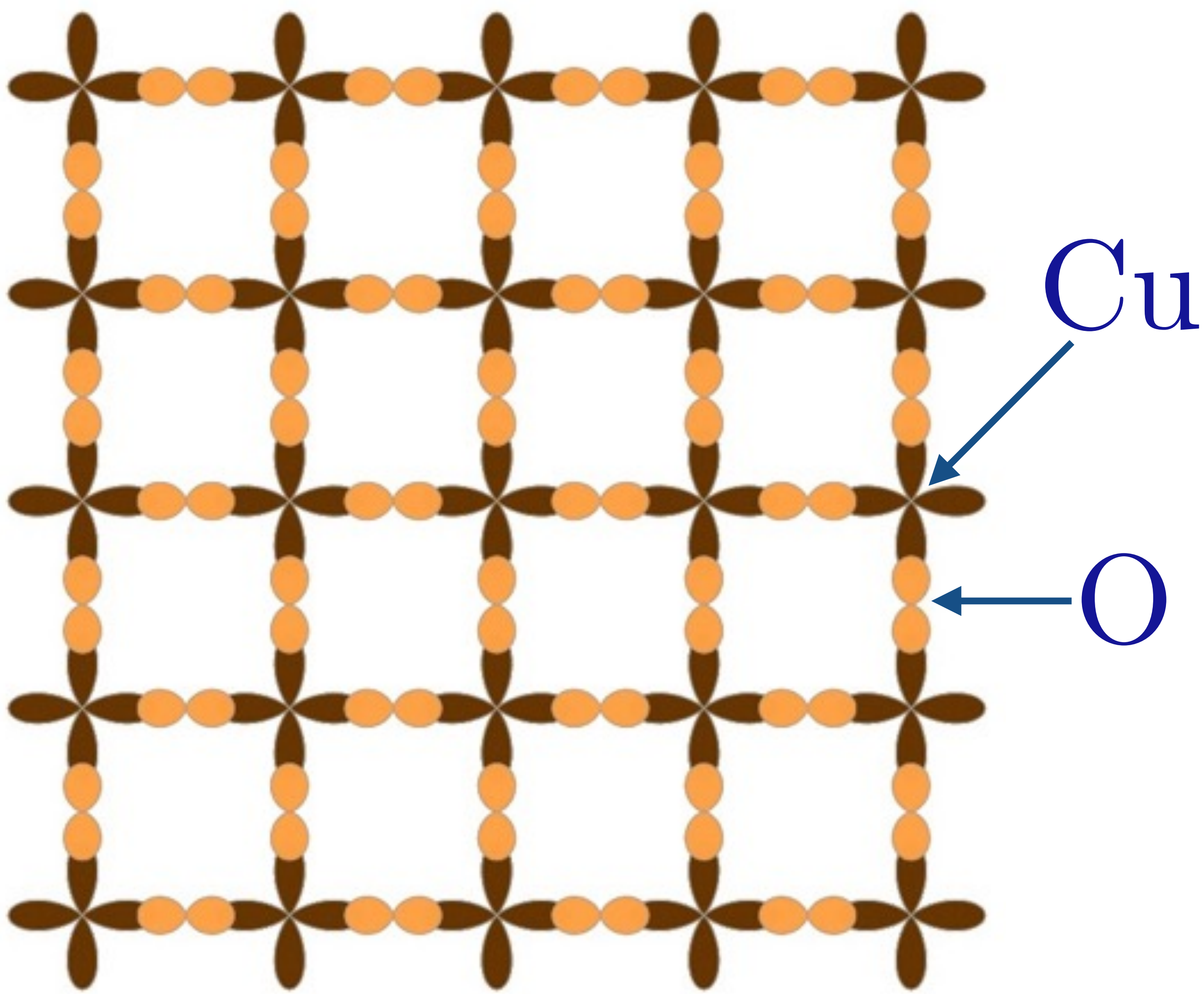
Electromagnetic gauge fields are needed to describe the long-range quantum entanglement of the "vacuum".

Modern point-of-view:

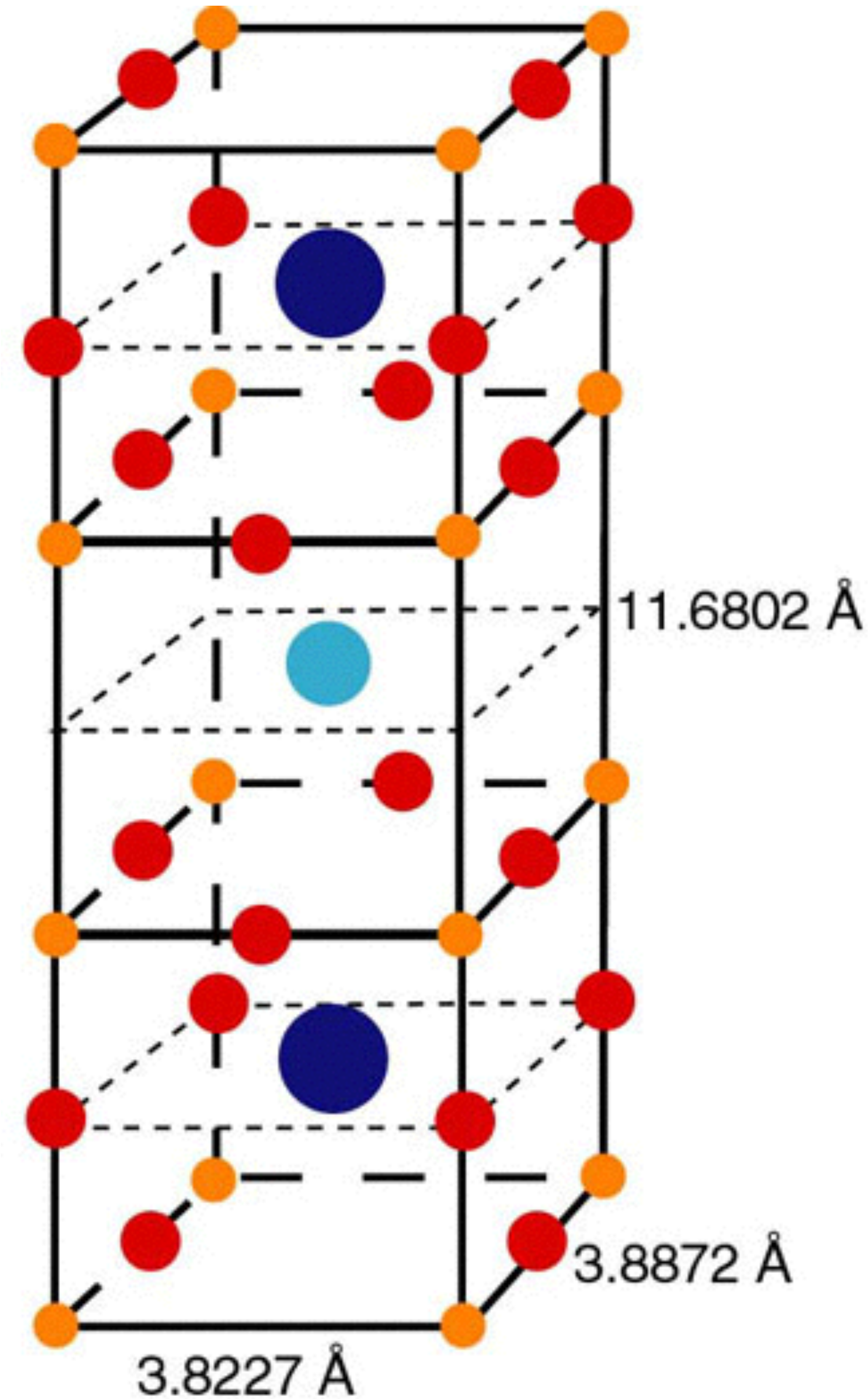
Electromagnetic gauge fields are needed to describe the long-range quantum entanglement of the "vacuum".

Electrons in crystals provide a new "vacuum", and their interactions can naturally lead to quantum states which have long-range quantum entanglement, and require "emergent" gauge fields.

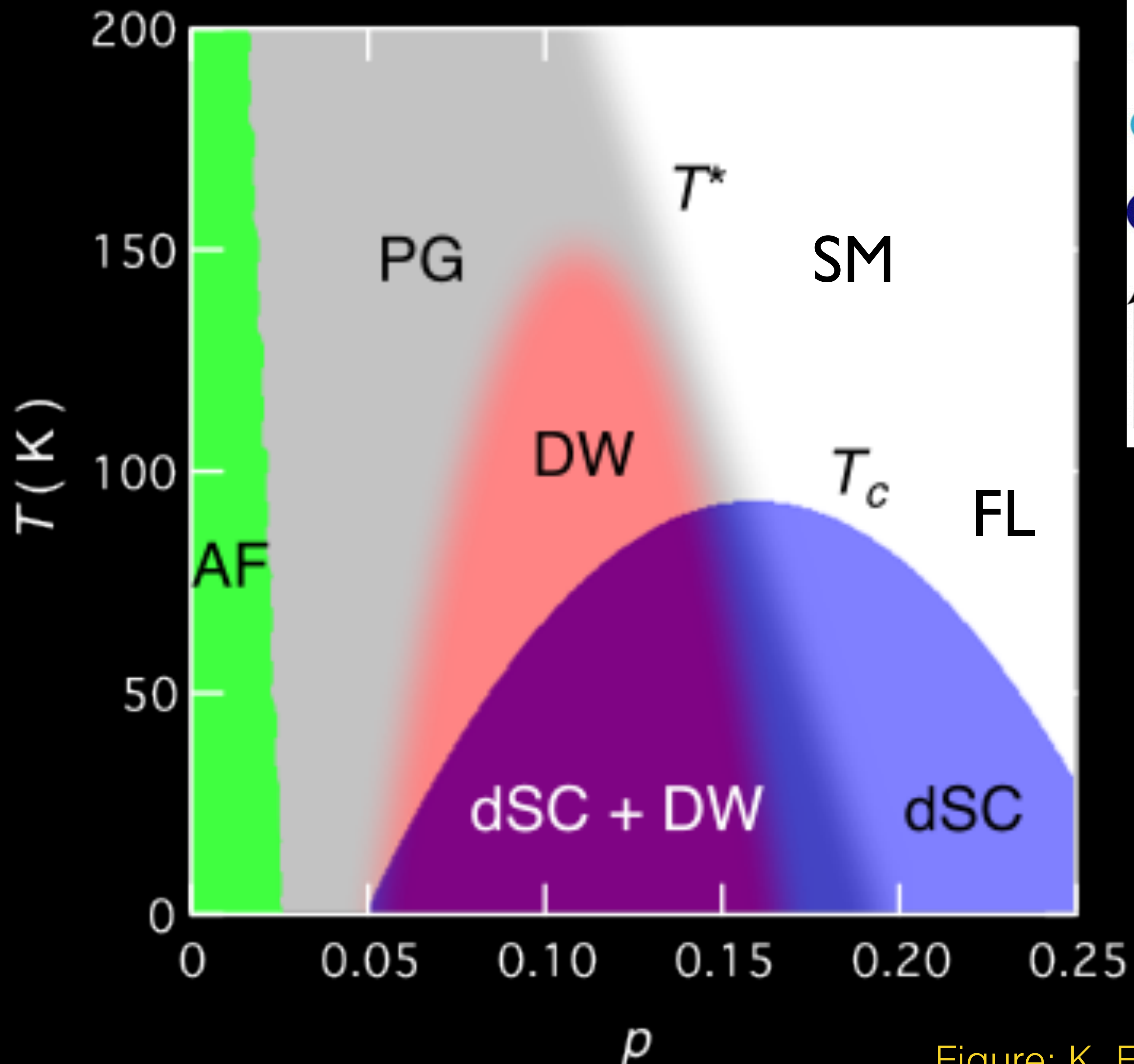
High temperature superconductors

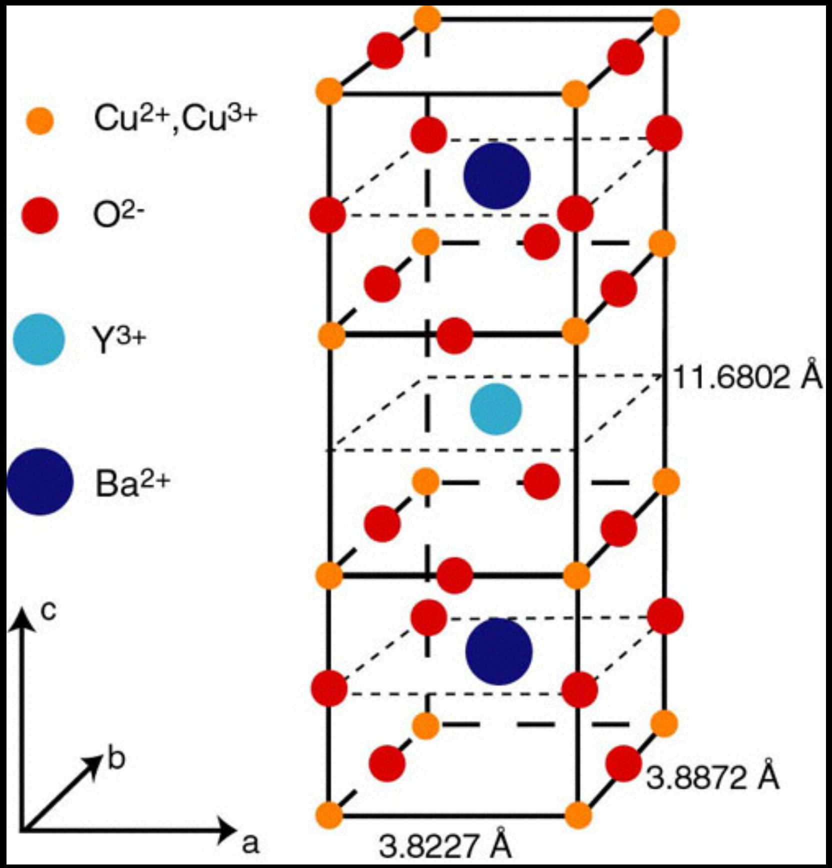


CuO_2 plane



$YBa_2Cu_3O_{6+x}$





$YBa_2Cu_3O_{6+x}$

Figure: K. Fujita and J. C. Seamus Davis

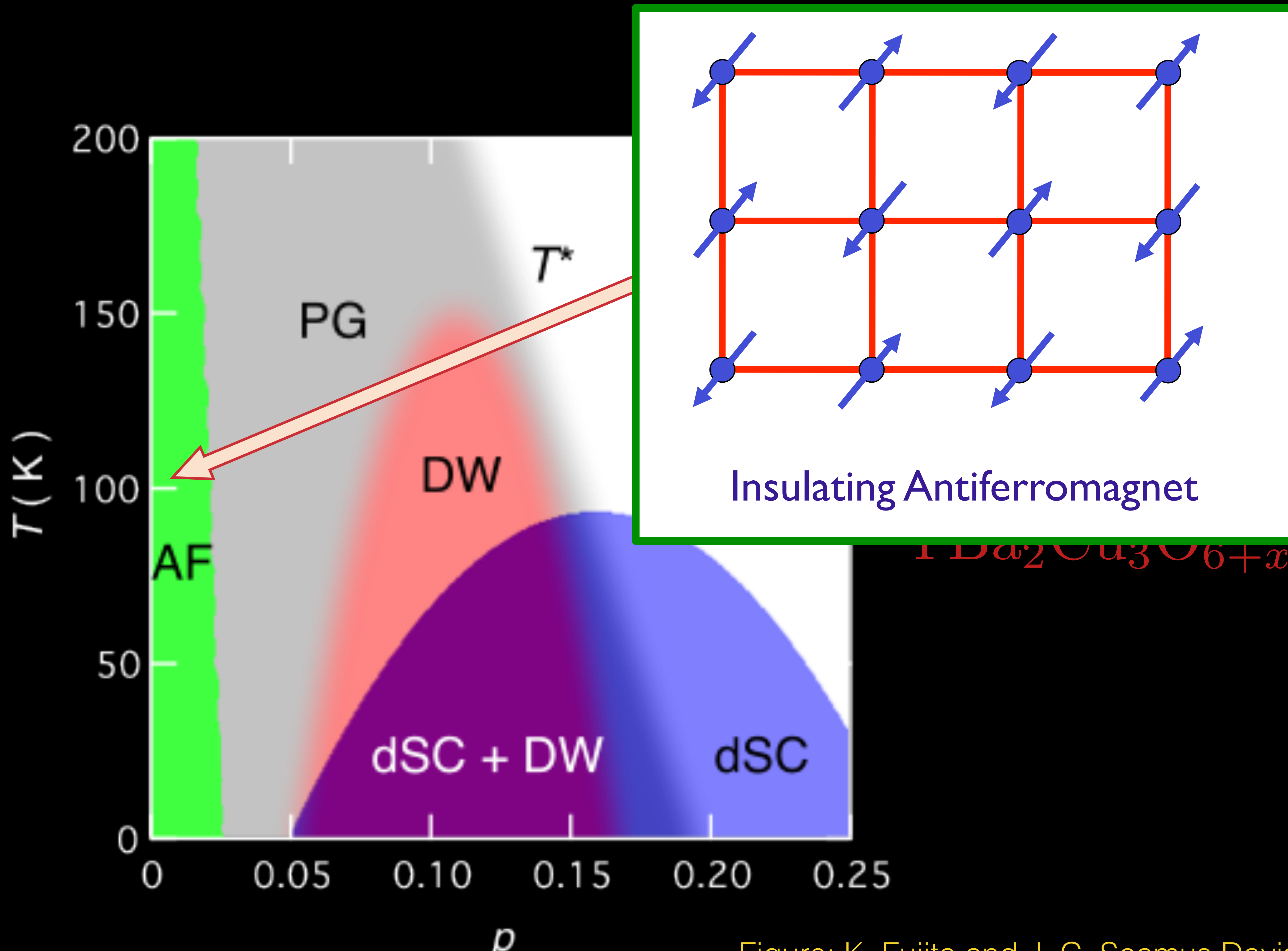
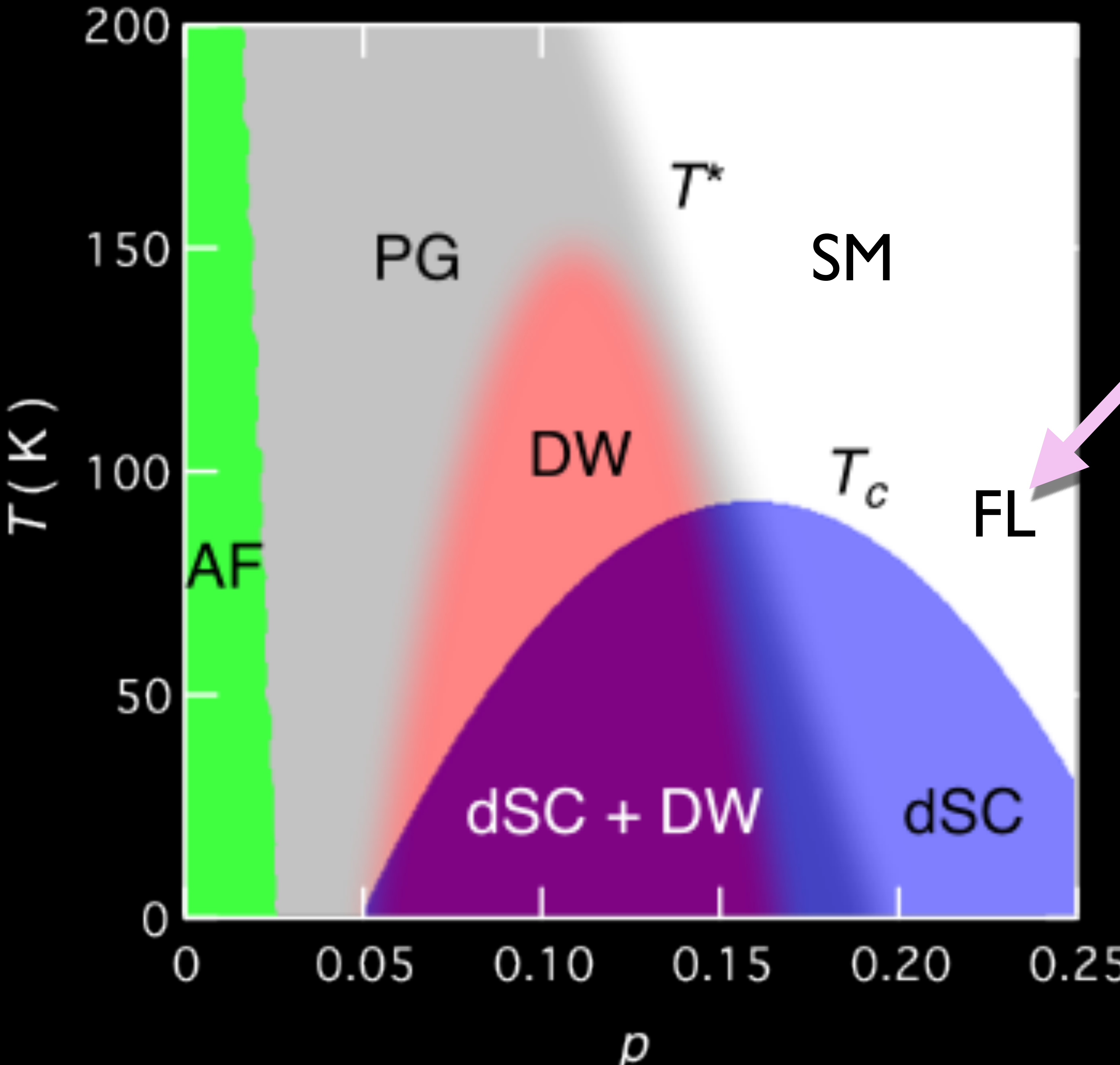
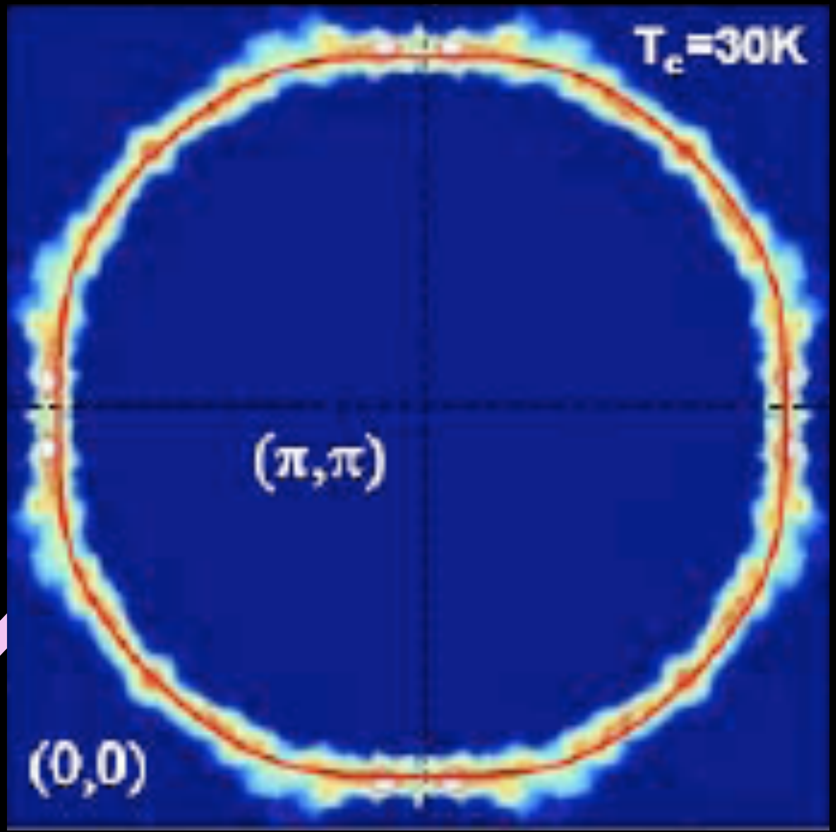


Figure: K. Fujita and J. C. Seamus Davis

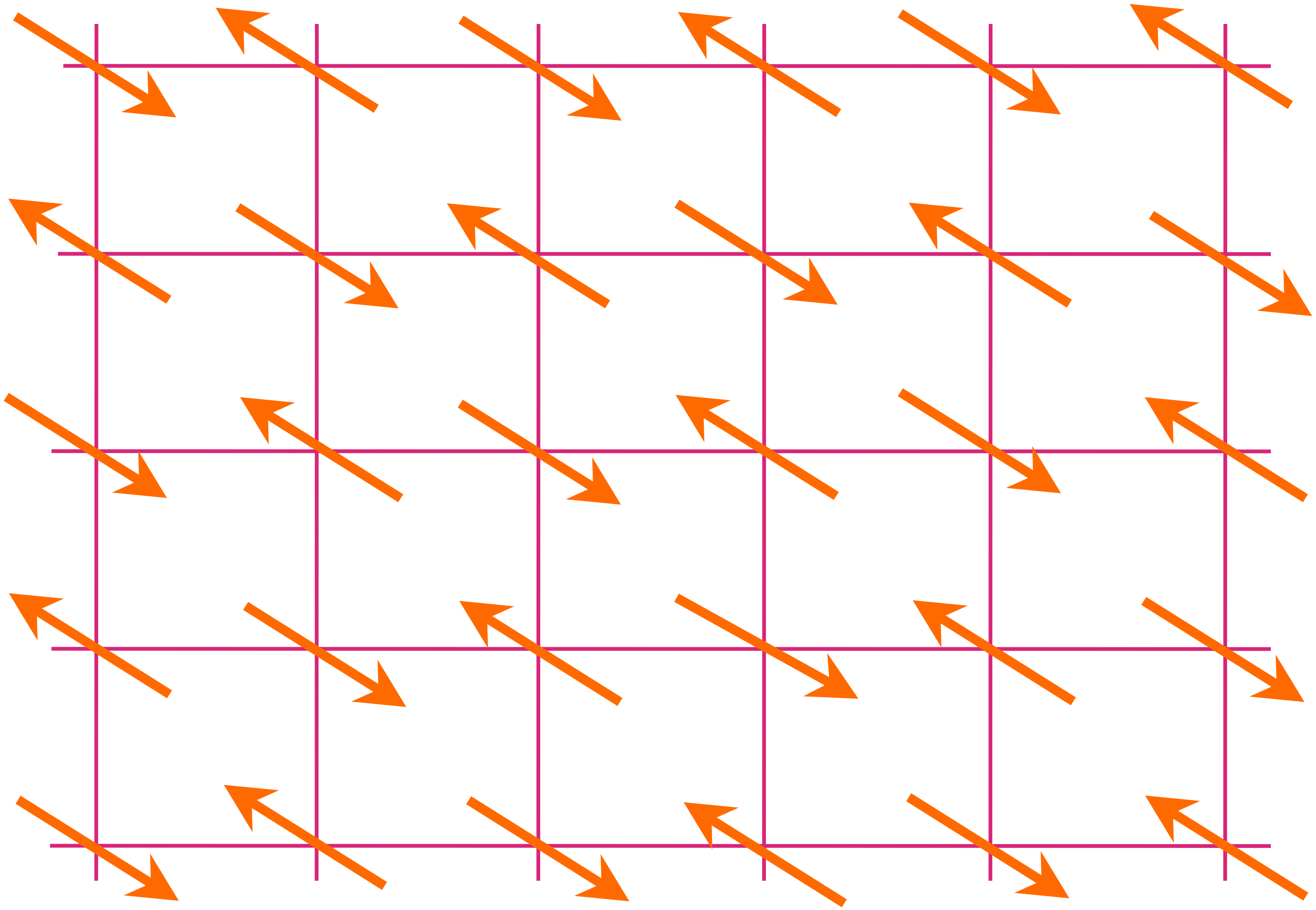
M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)





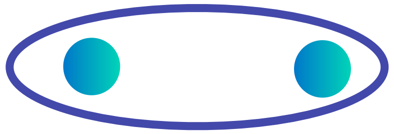
A conventional metal: the Fermi liquid

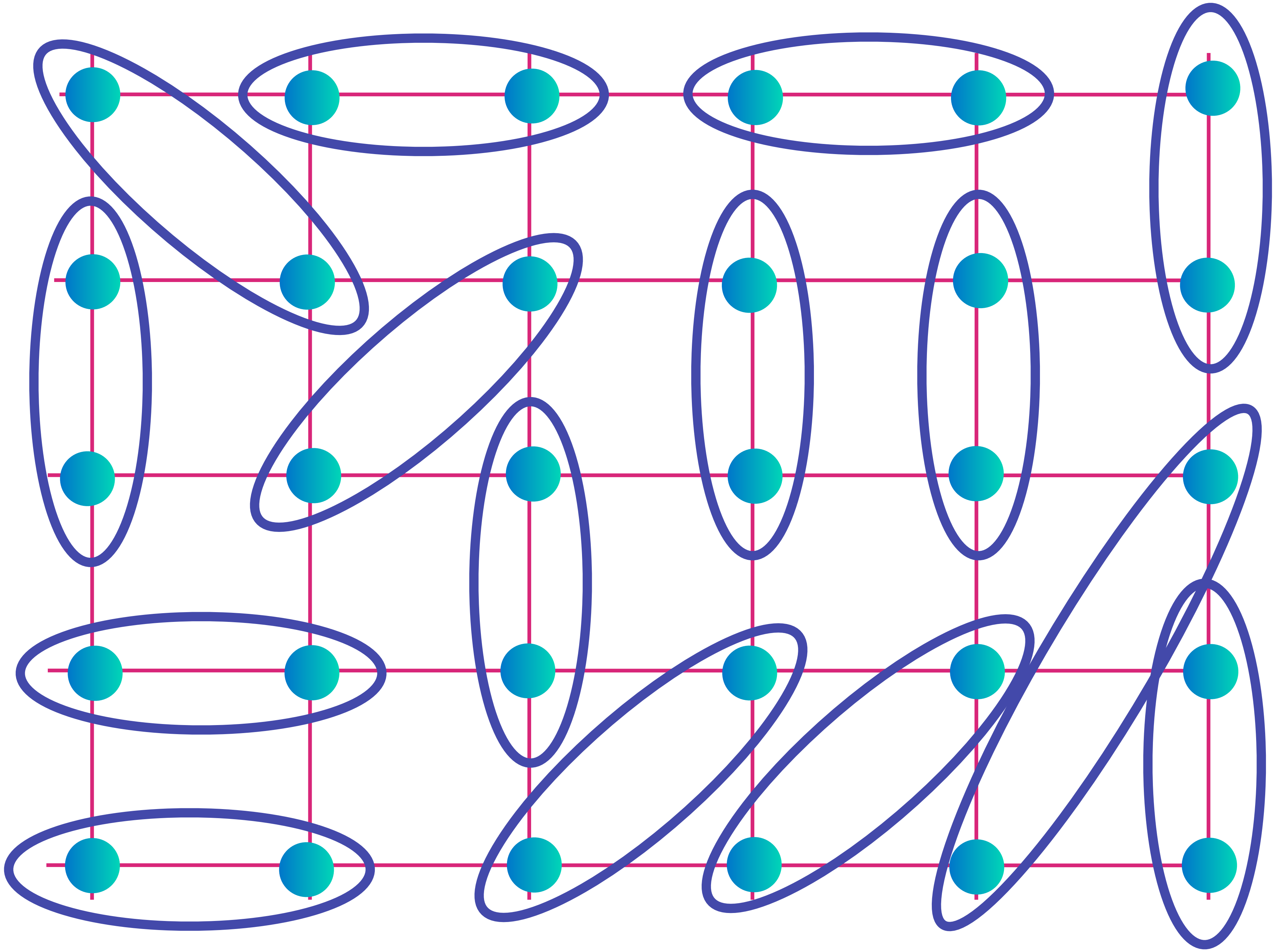
1. Emergent gauge fields and long-range entanglement in insulators



"Undoped"
Anti-
ferromagnet

Insulating spin liquid

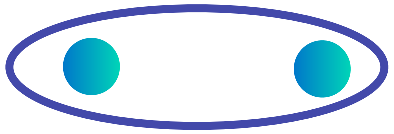

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

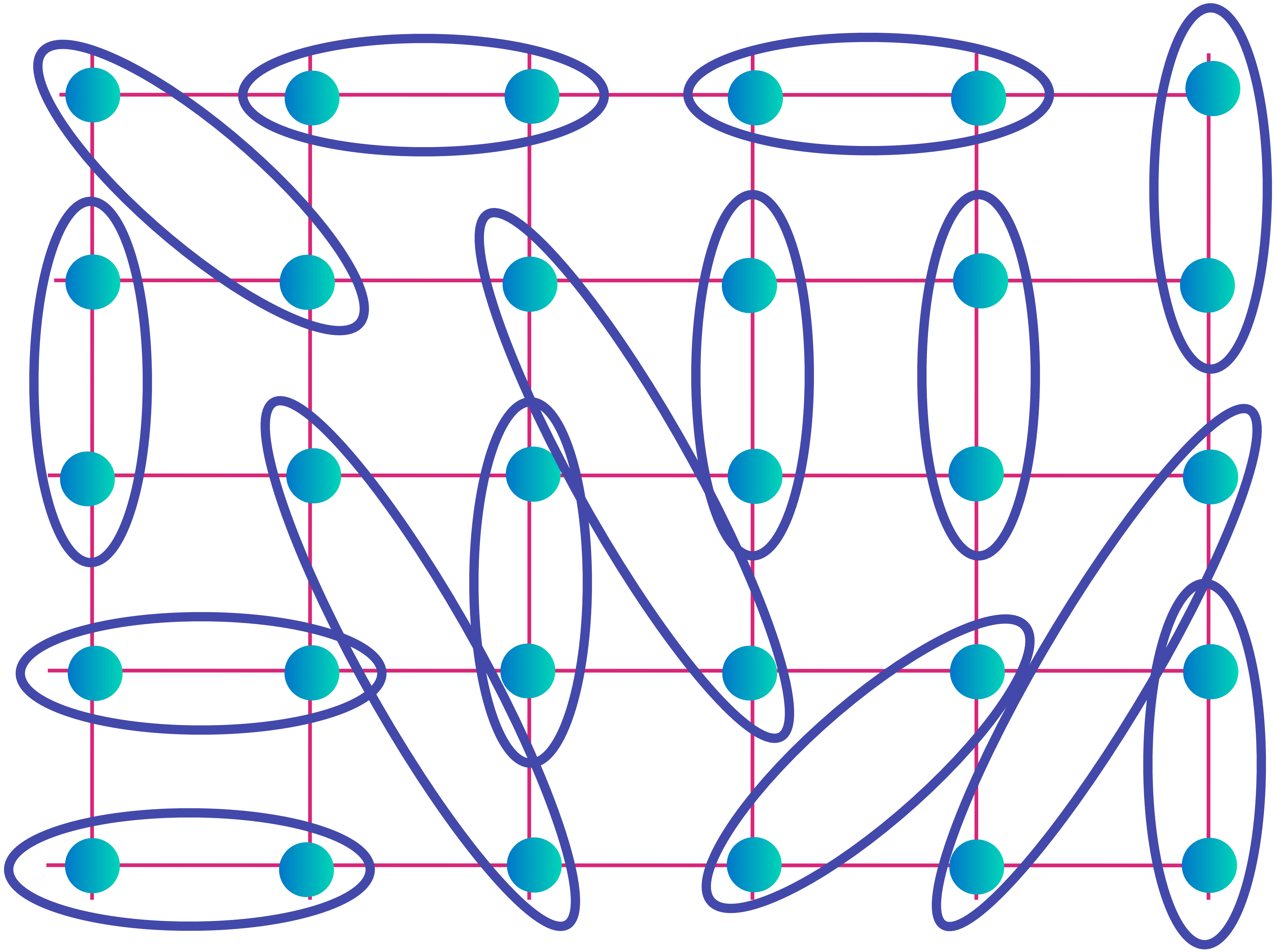


An insulator with emergent gauge fields: the first proposal of a quantum state with long-range entanglement

L. Pauling, Proceedings of the Royal Society London A **196**, 343 (1949)
P.W. Anderson, Materials Research Bulletin **8**, 153 (1973)

Insulating spin liquid

 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

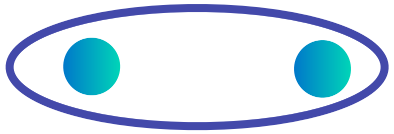


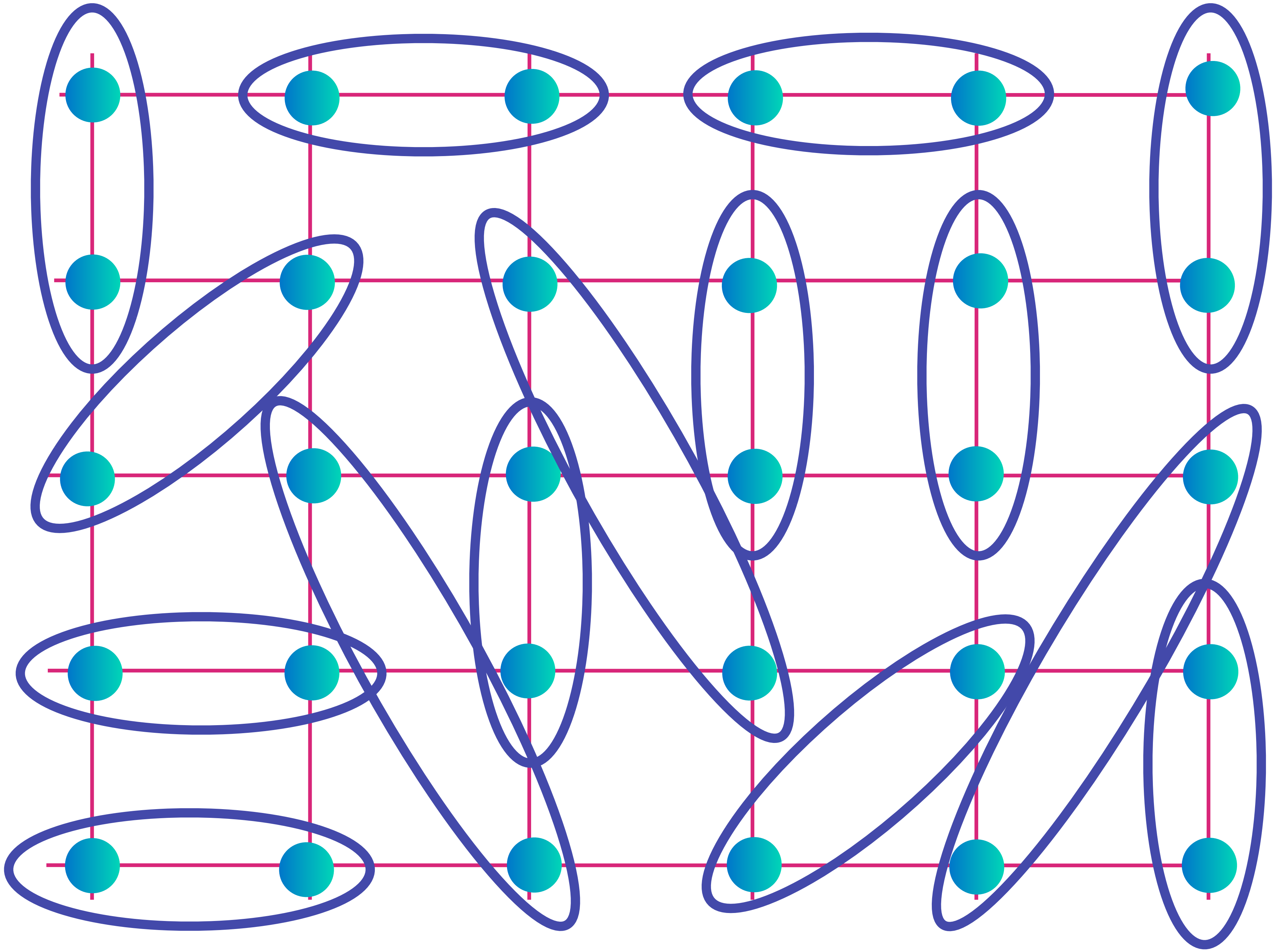
An insulator with emergent gauge fields: the first proposal of a quantum state with long-range entanglement

L. Pauling, Proceedings of the Royal Society London A **196**, 343 (1949)

P.W. Anderson, Materials Research Bulletin **8**, 153 (1973)

Insulating spin liquid

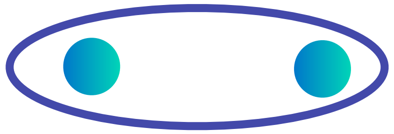
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



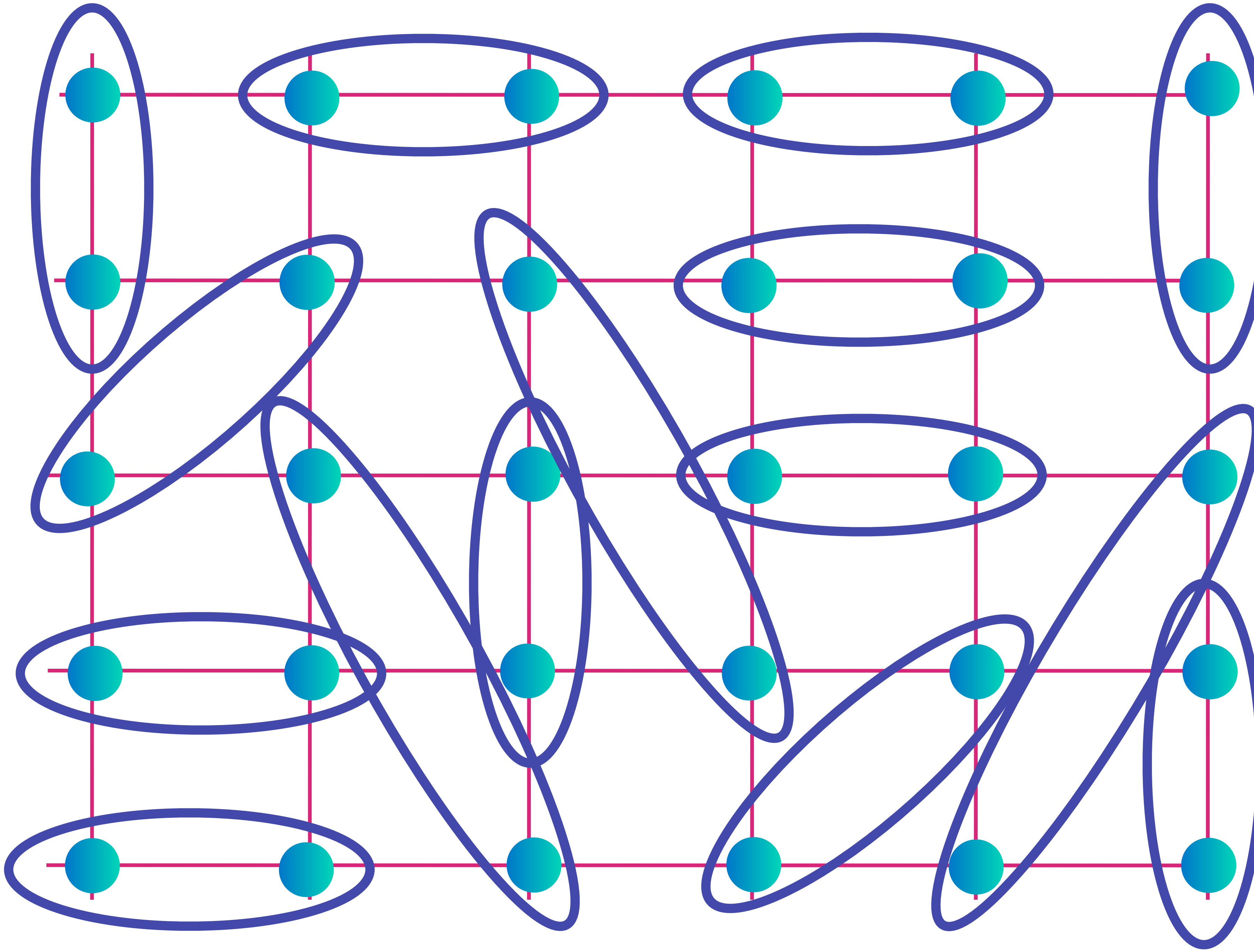
An insulator with emergent gauge fields: the first proposal of a quantum state with long-range entanglement

L. Pauling, Proceedings of the Royal Society London A **196**, 343 (1949)
P.W. Anderson, Materials Research Bulletin **8**, 153 (1973)

Insulating spin liquid



$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

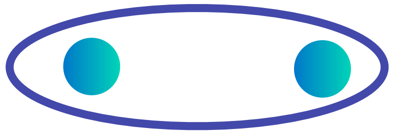


An insulator with emergent gauge fields: the first proposal of a quantum state with long-range entanglement

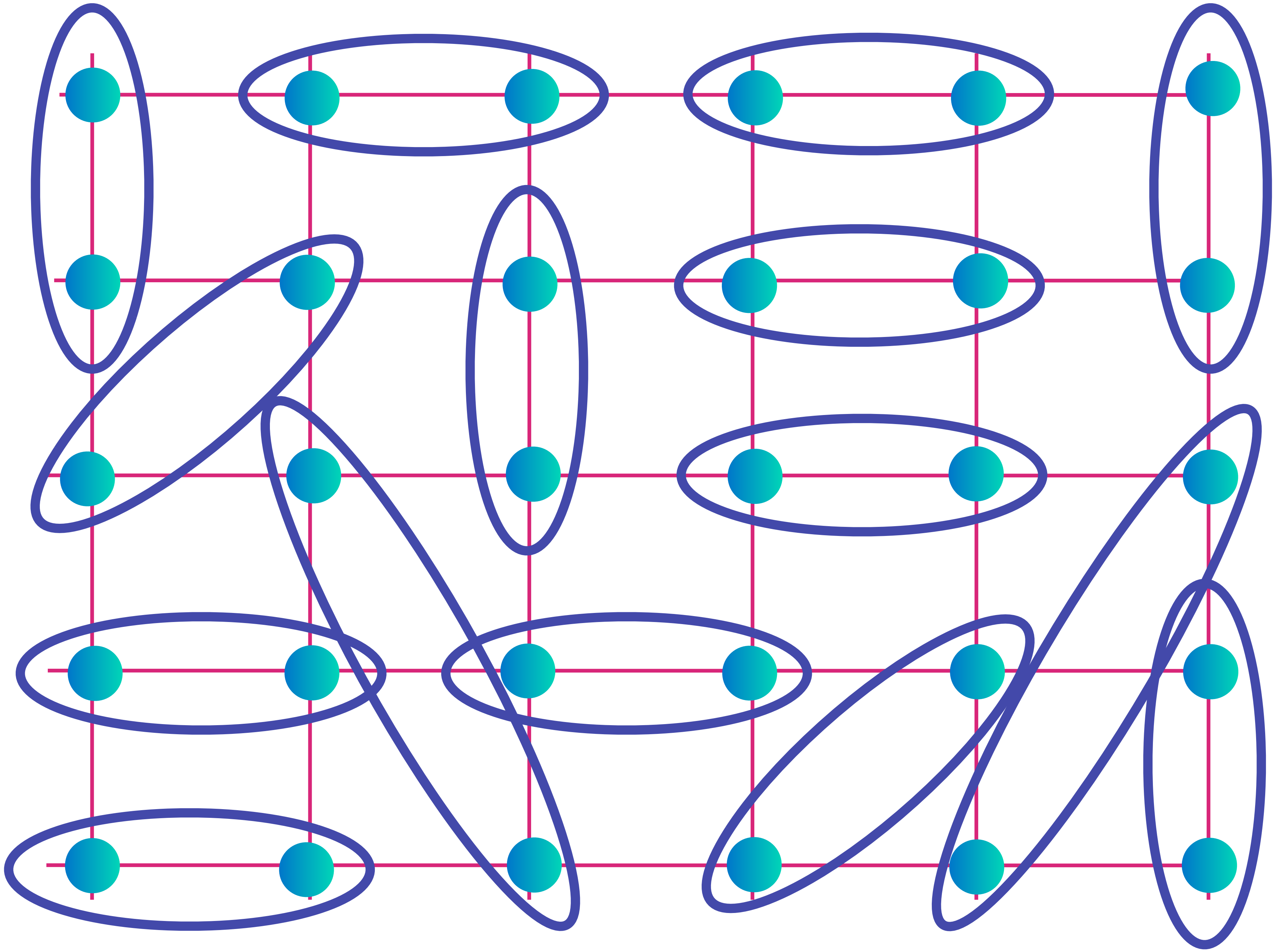
L. Pauling, Proceedings of the Royal Society London A **196**, 343 (1949)

P.W. Anderson, Materials Research Bulletin **8**, 153 (1973)

Insulating spin liquid



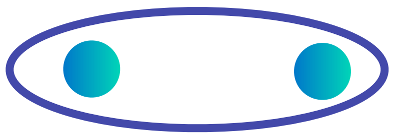
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$



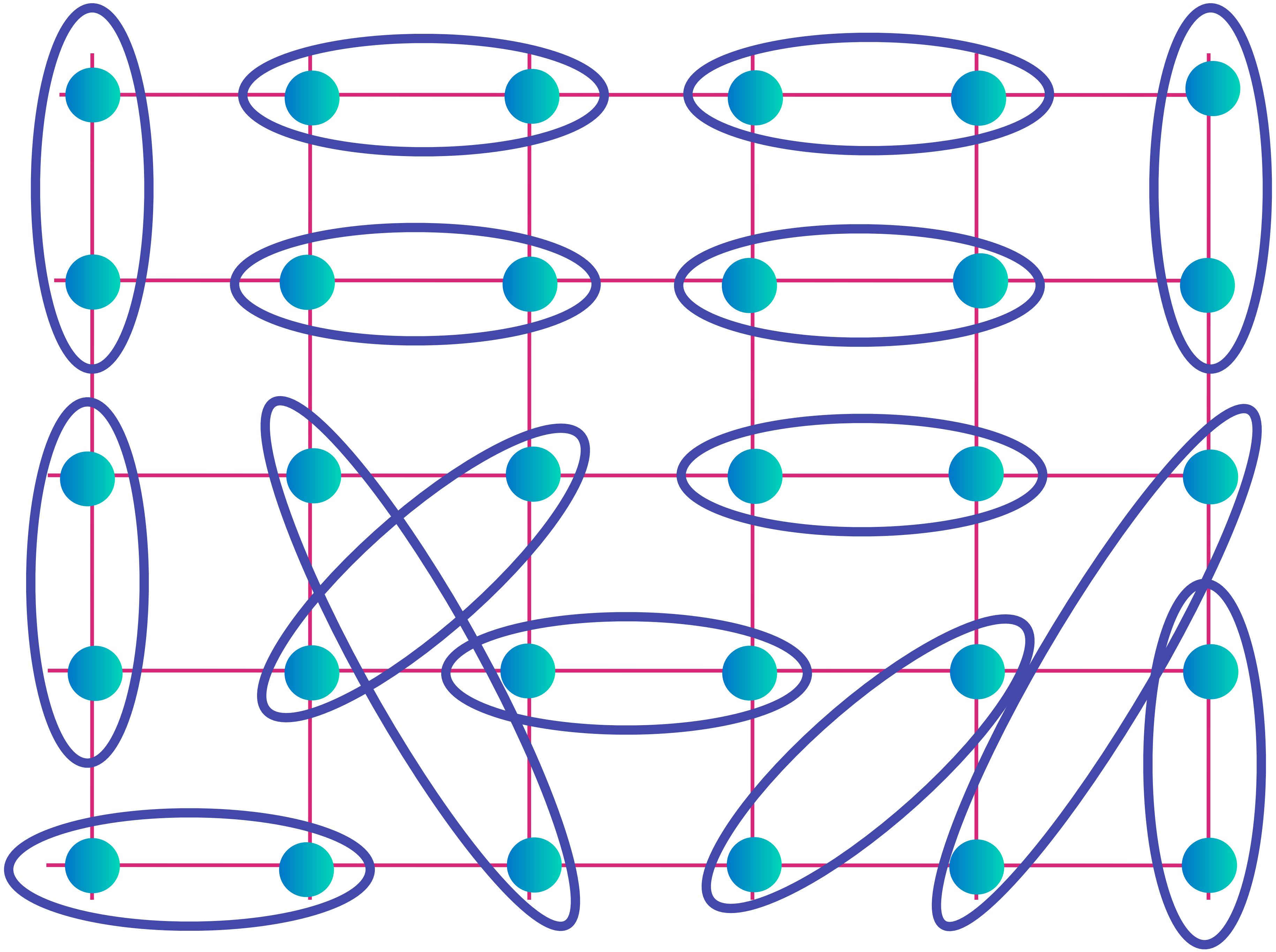
An insulator with emergent gauge fields: the first proposal of a quantum state with long-range entanglement

L. Pauling, Proceedings of the Royal Society London A **196**, 343 (1949)
P.W. Anderson, Materials Research Bulletin **8**, 153 (1973)

Insulating spin liquid



$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



An insulator with emergent gauge fields: the first proposal of a quantum state with long-range entanglement

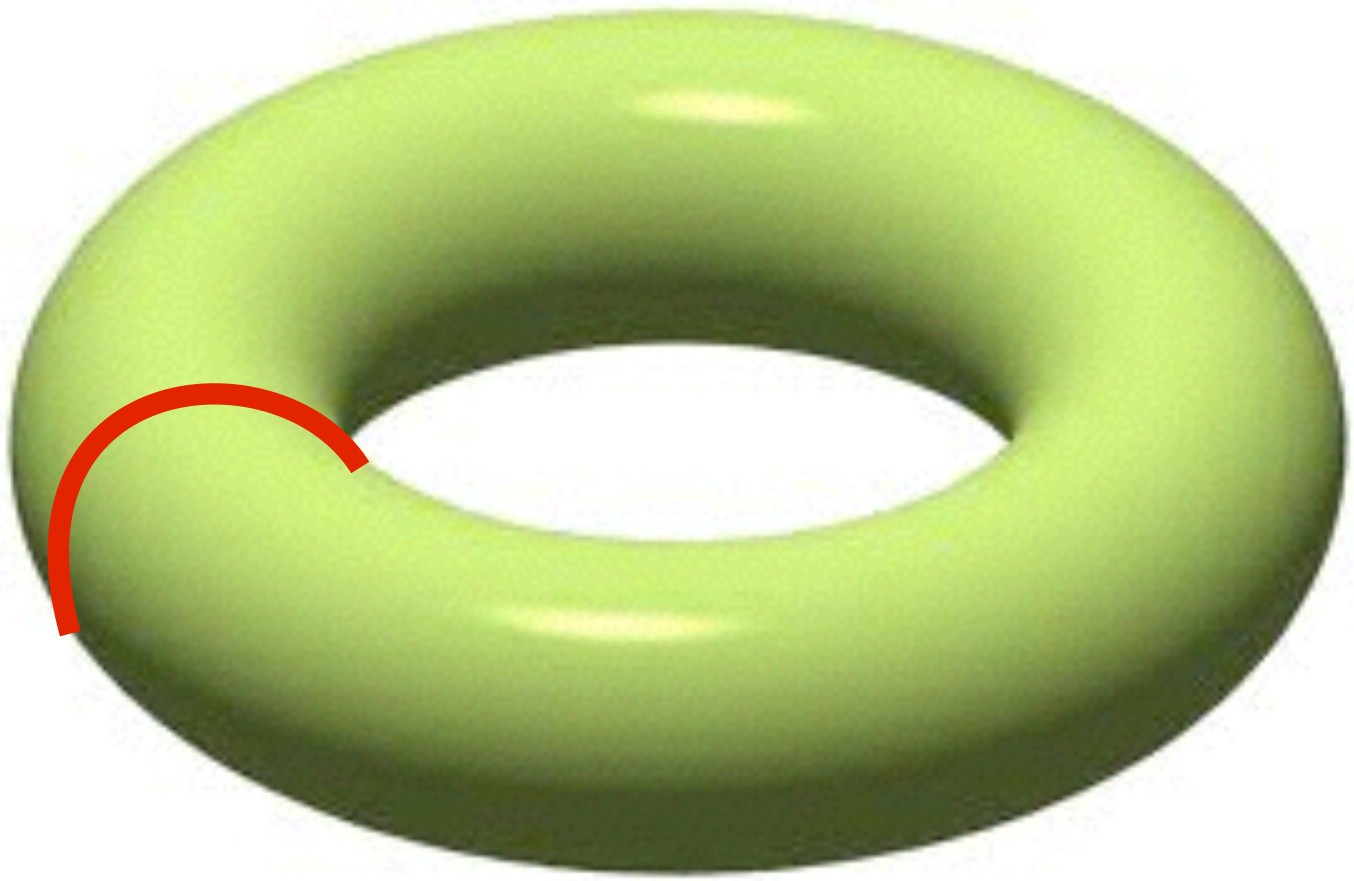
L. Pauling, Proceedings of the Royal Society London A **196**, 343 (1949)

P.W. Anderson, Materials Research Bulletin **8**, 153 (1973)

Ground state degeneracy

Place insulator on a torus;

Ground state degeneracy



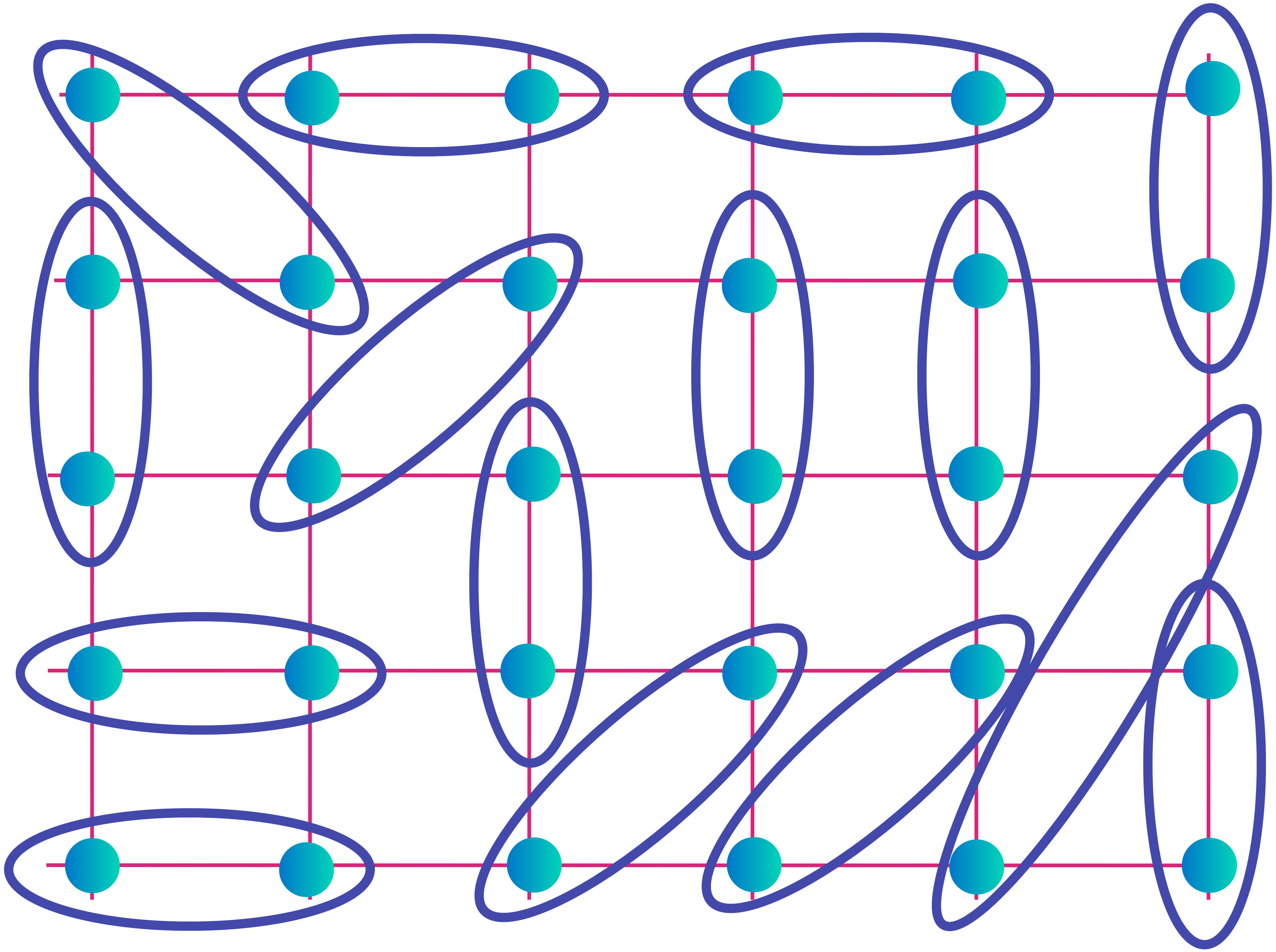
Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$



Place insulator on a torus;

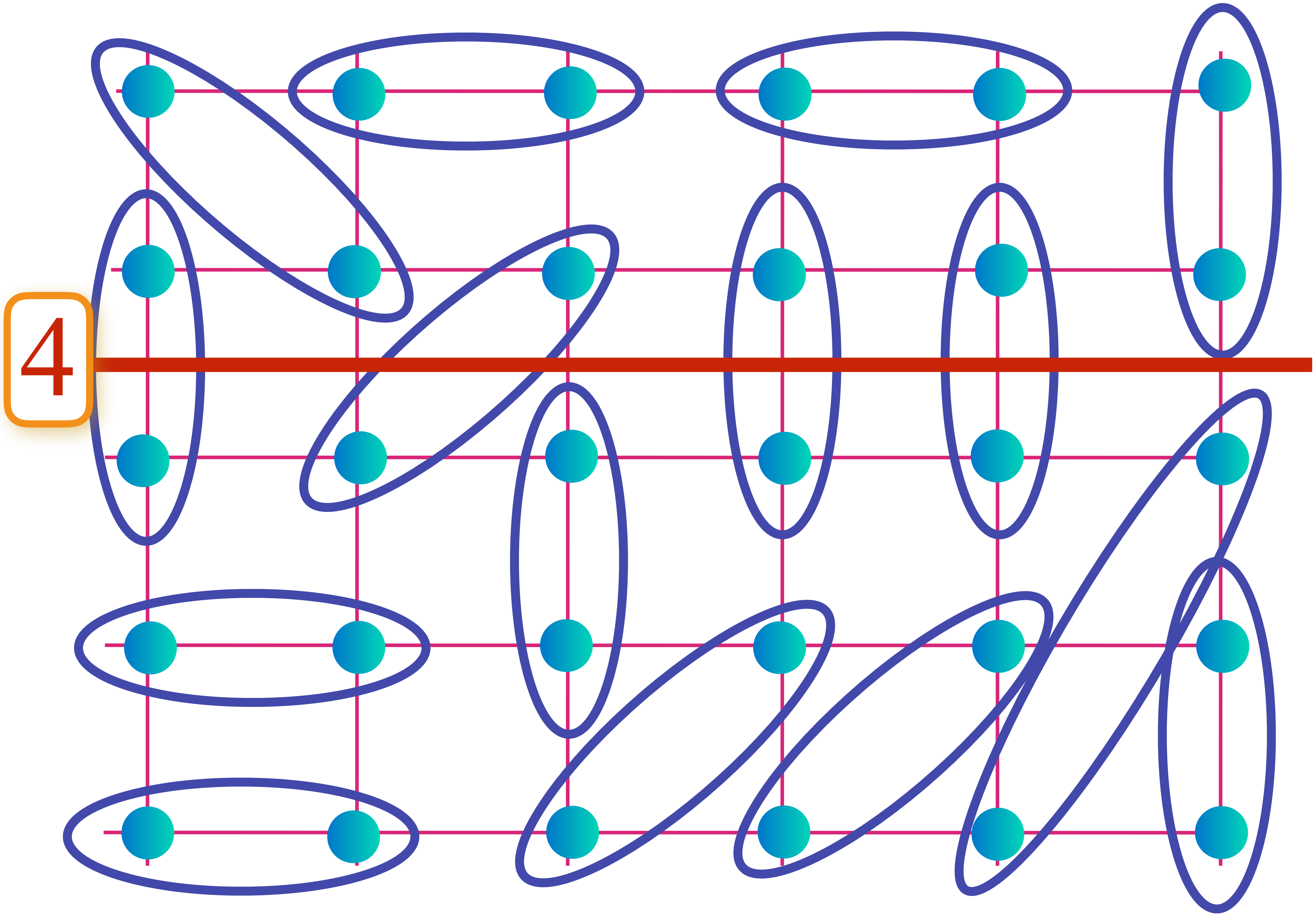
obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

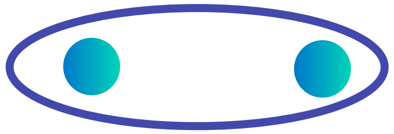


Place insulator on a torus;

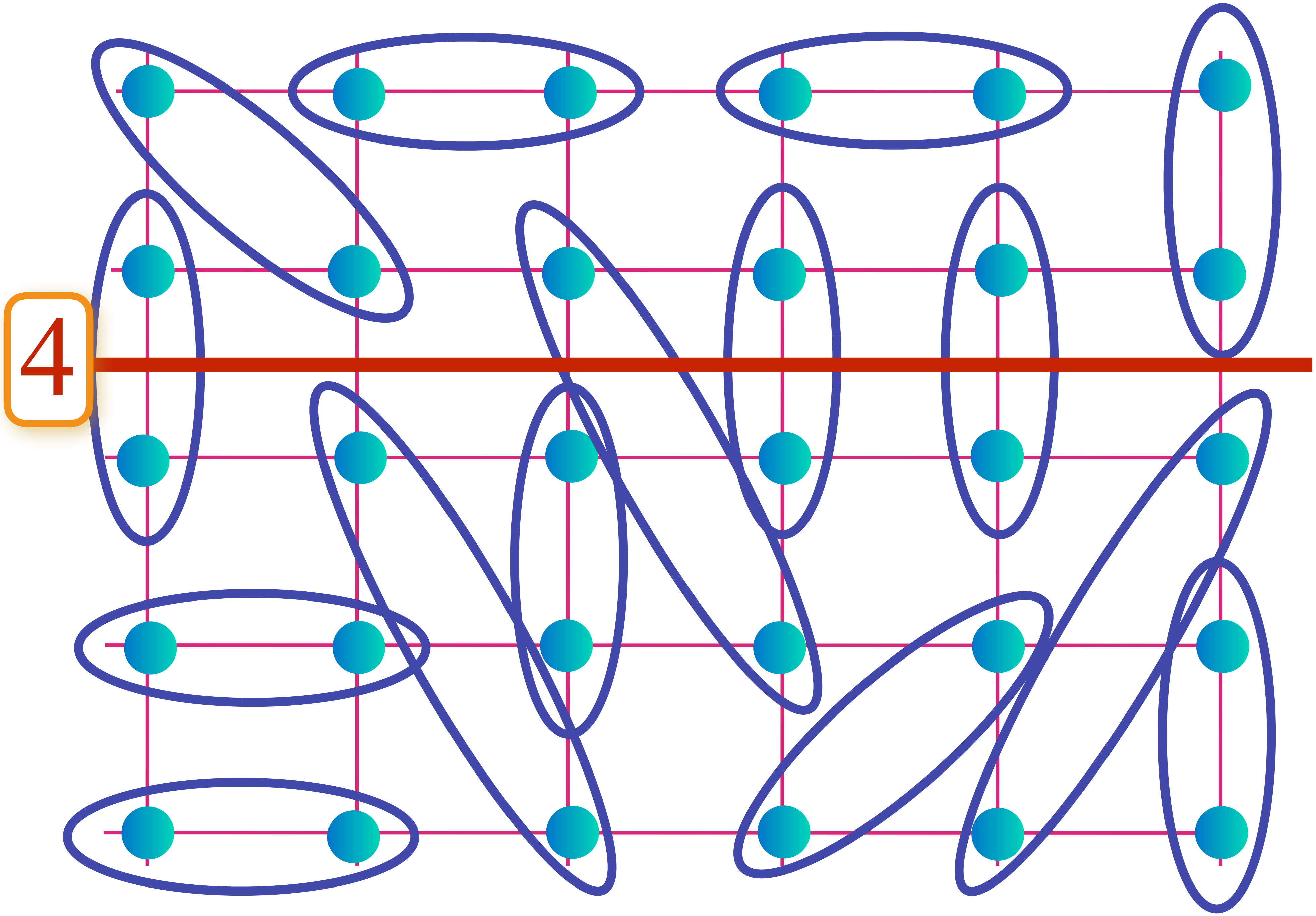
obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy



$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

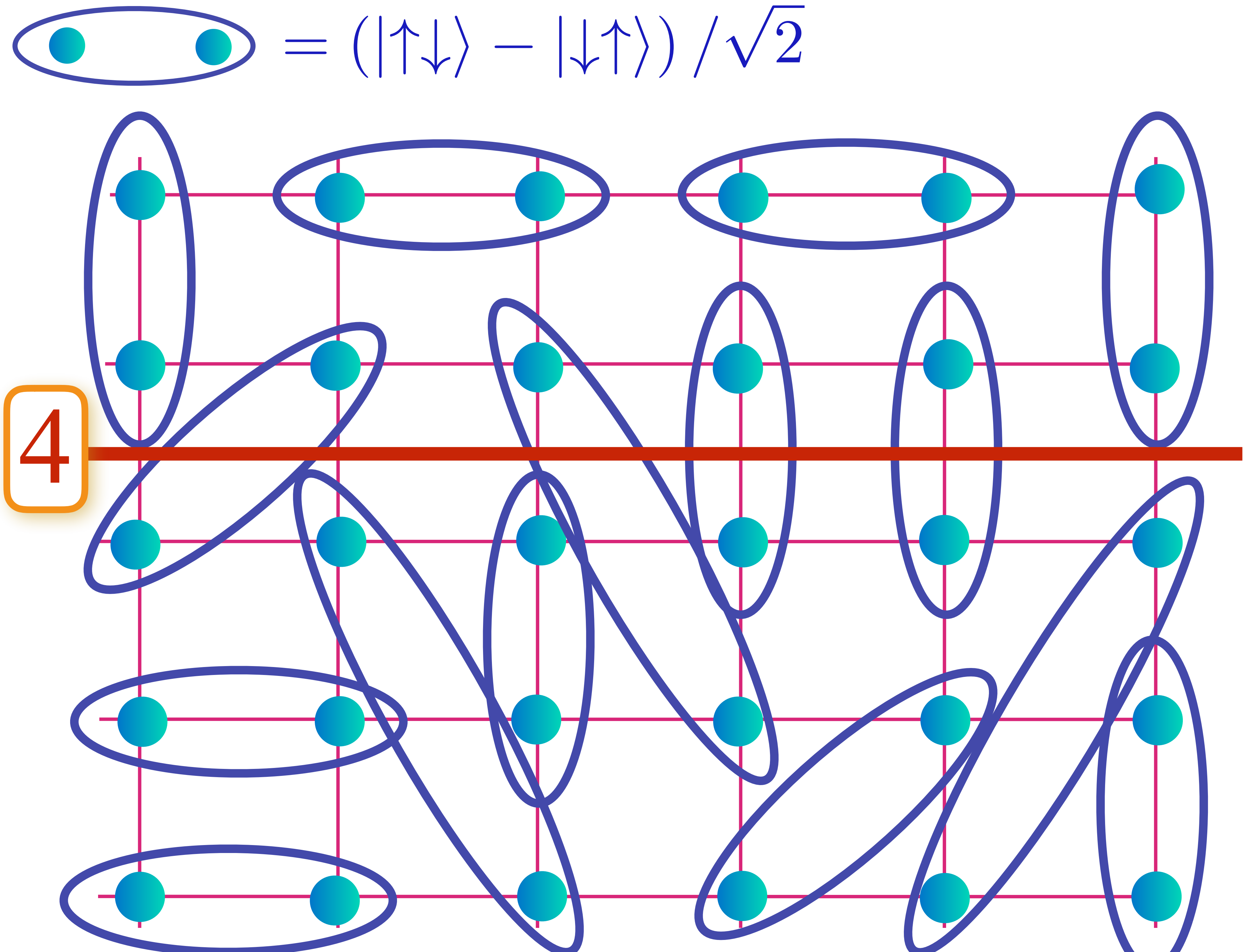


Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

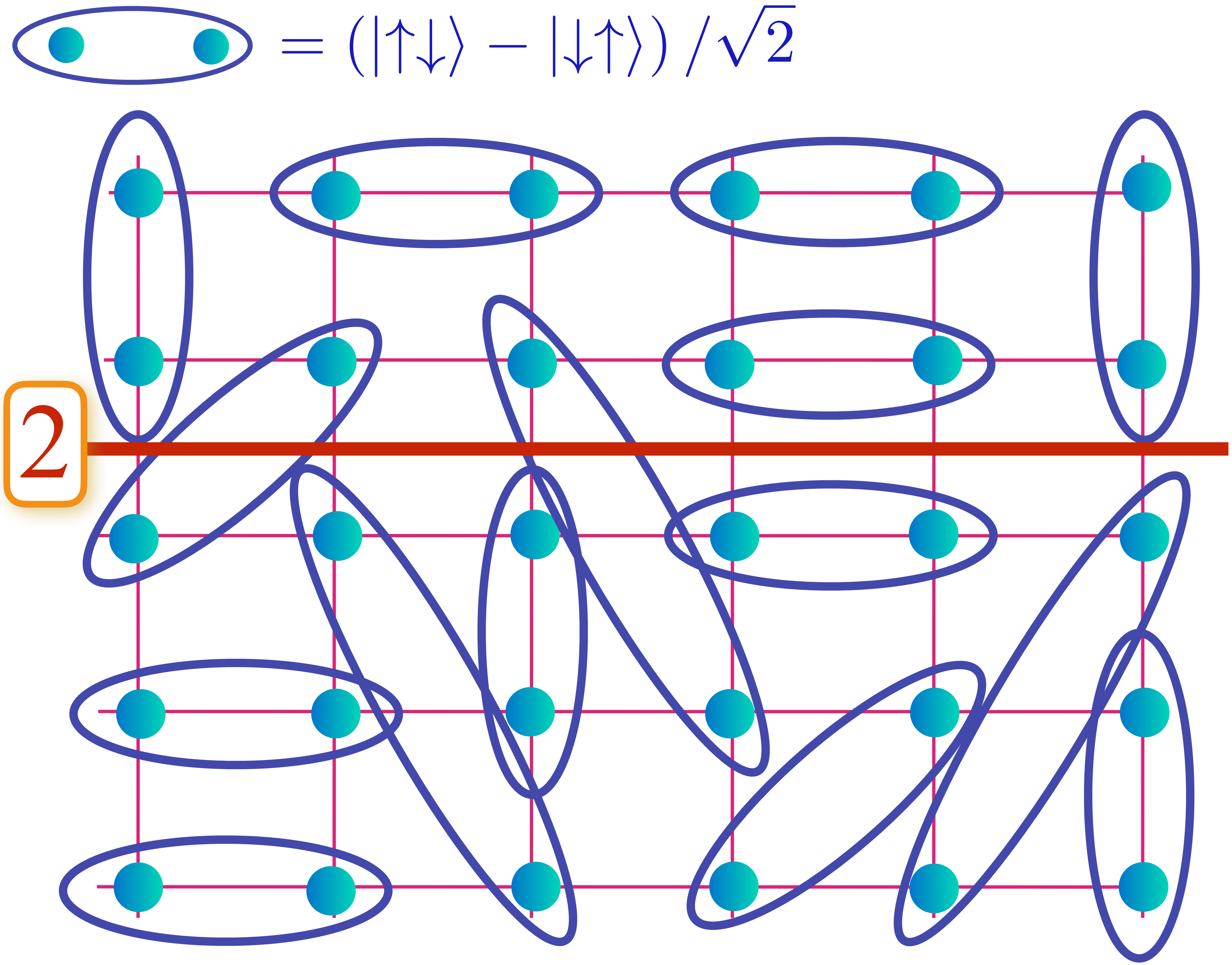


Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

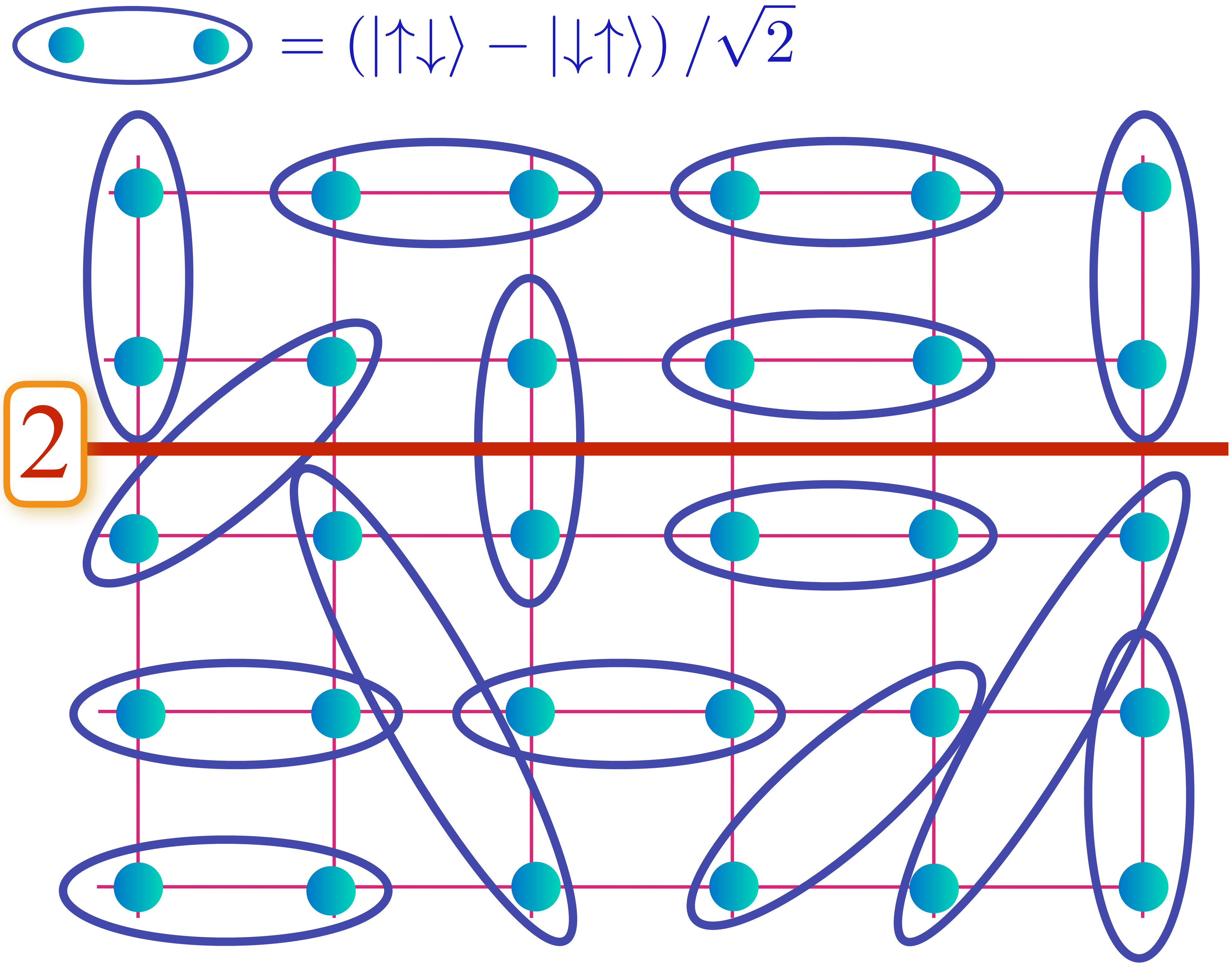


Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

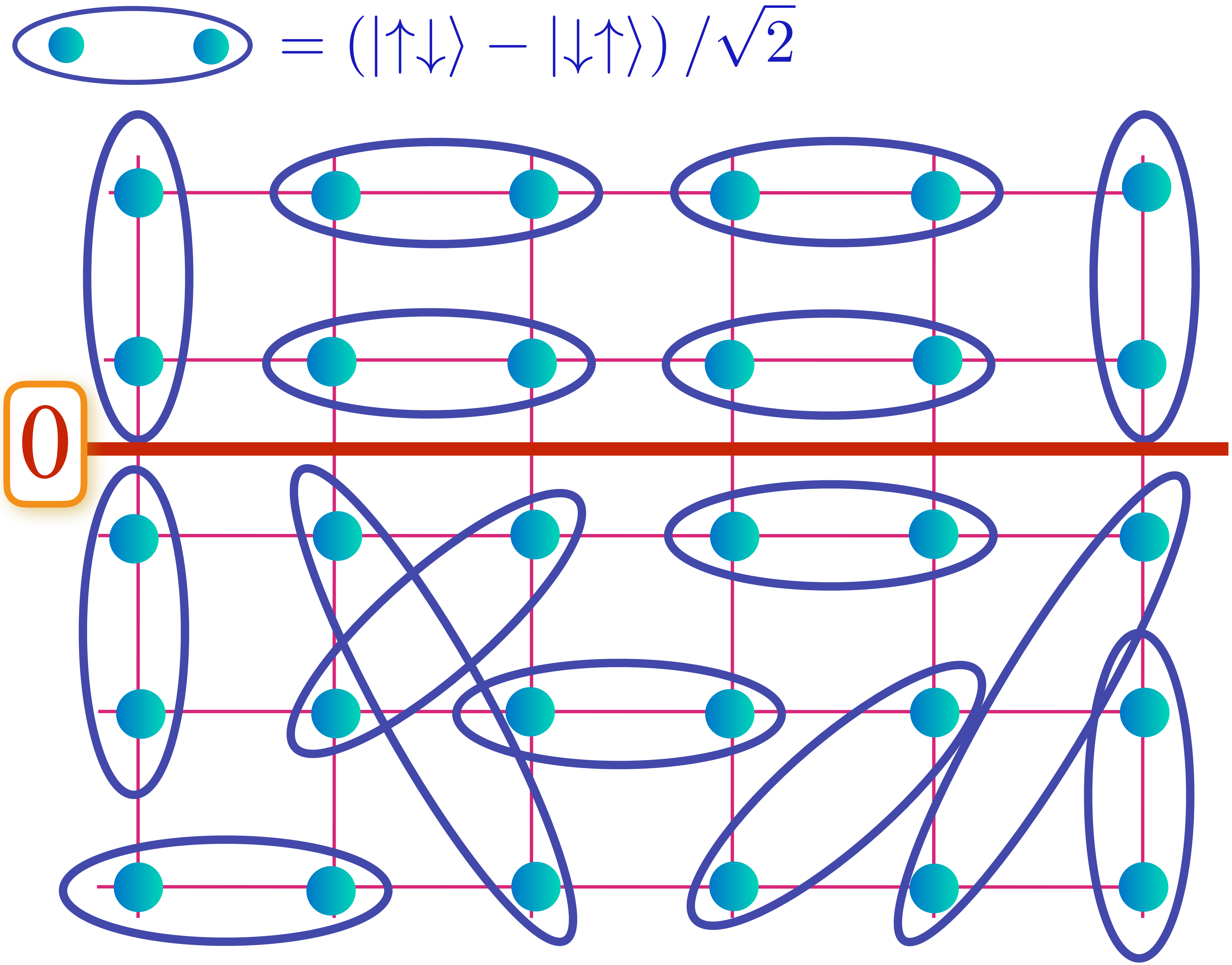


Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

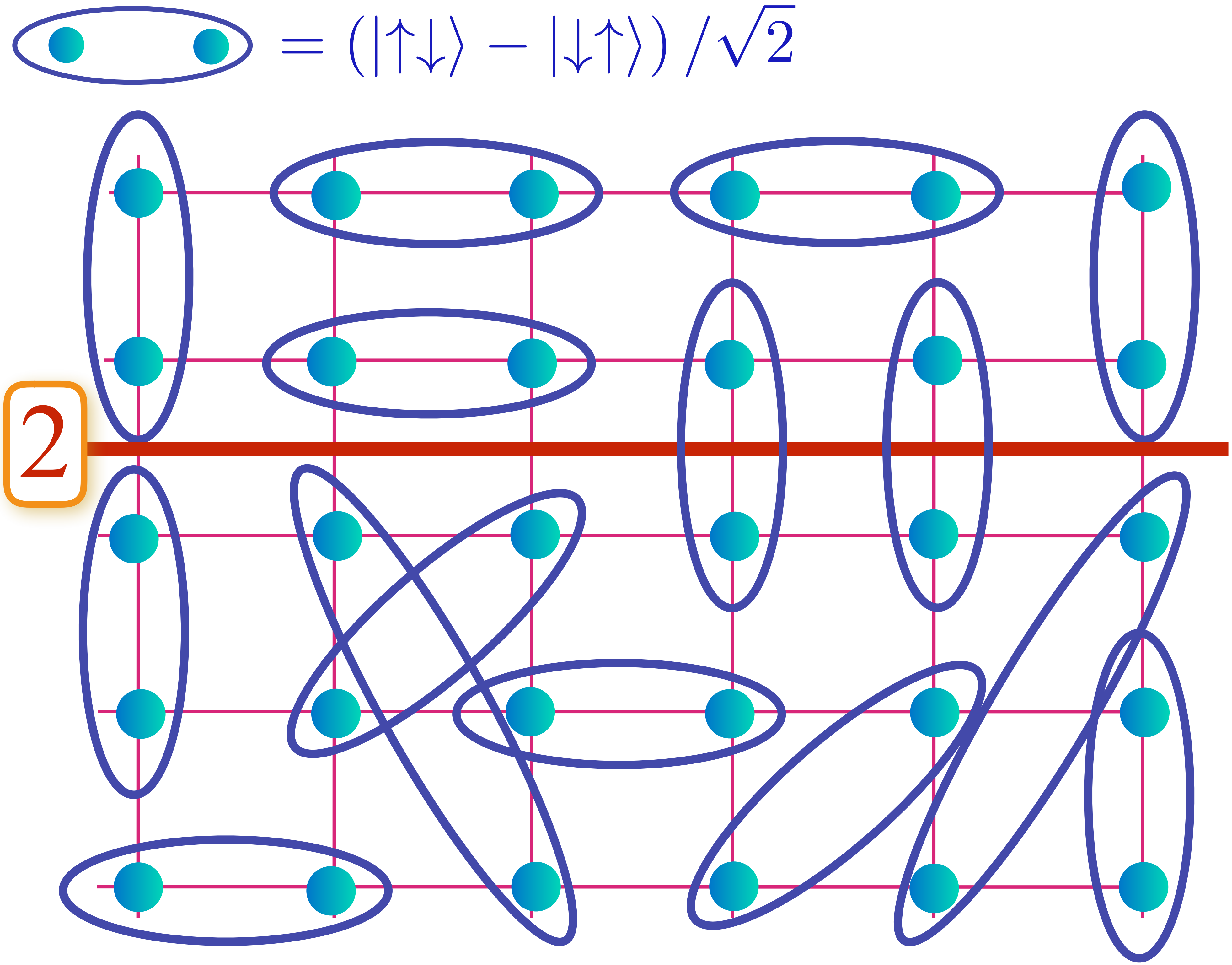


Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

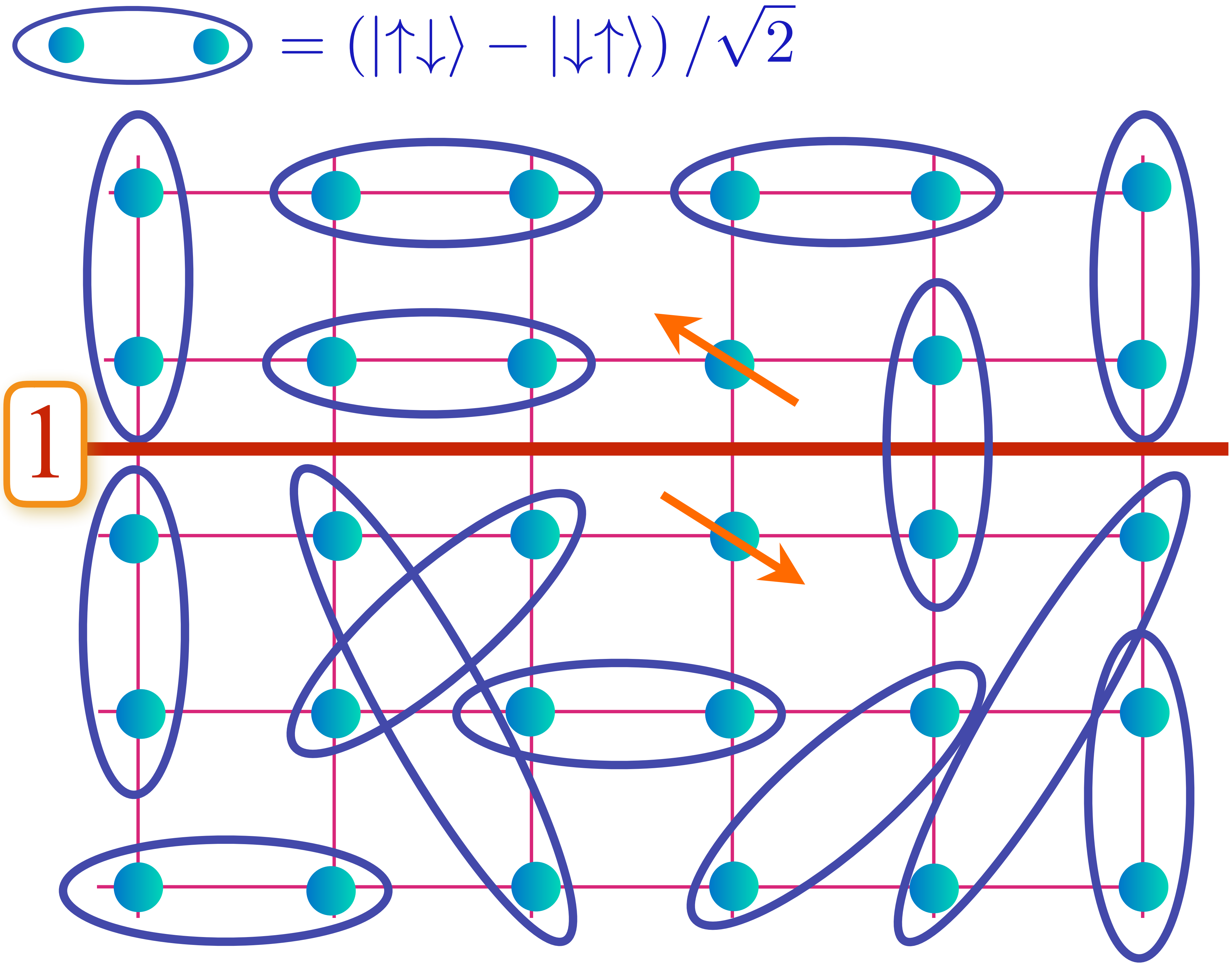


Place insulator on a torus;

obtain "topological" states nearly degenerate with the ground state: number of dimers crossing red line is conserved modulo 2

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

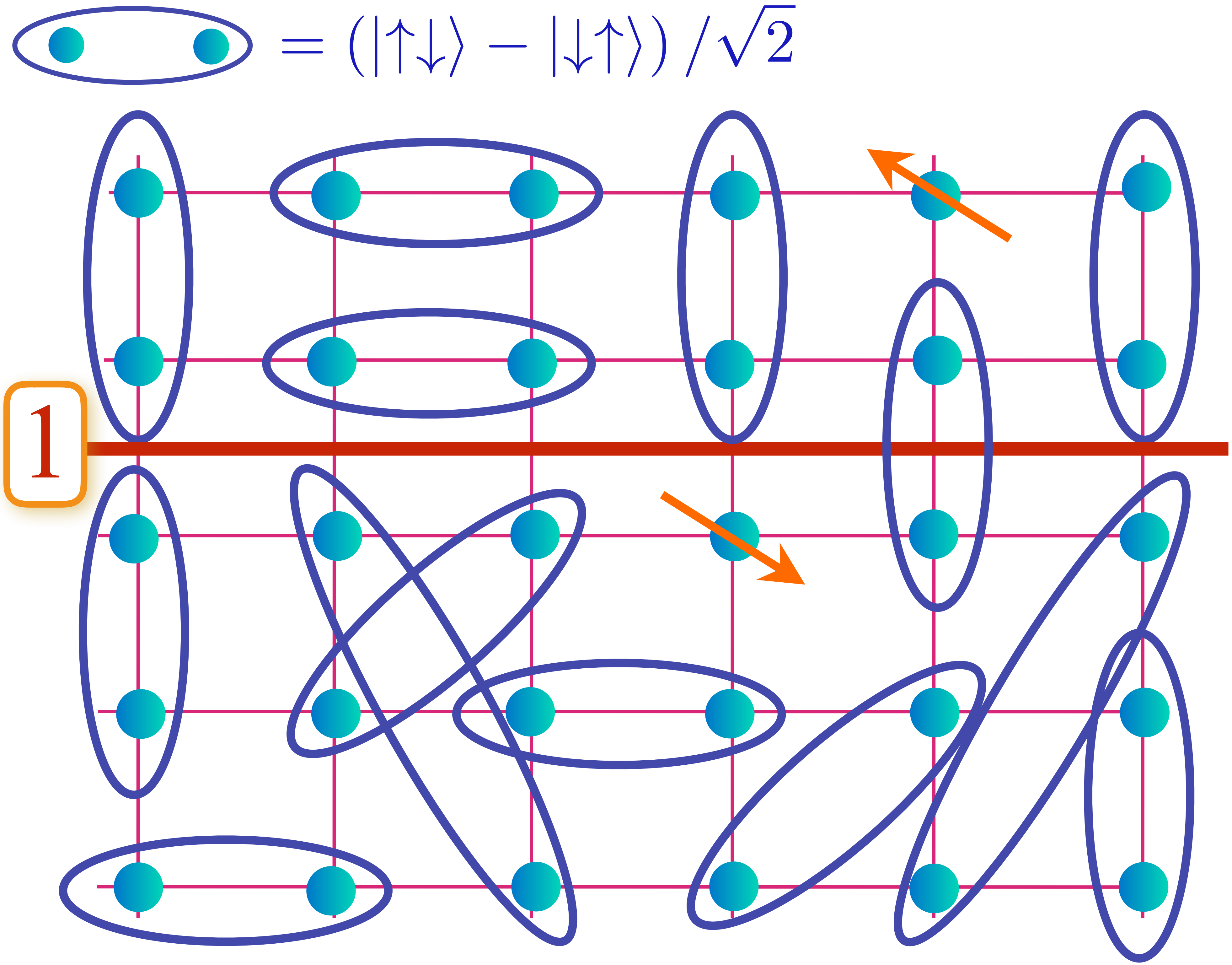


Place insulator on a torus;

to change dimer number parity across red line, it is necessary to create a pair of unpaired spins and move them around the sample.

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy



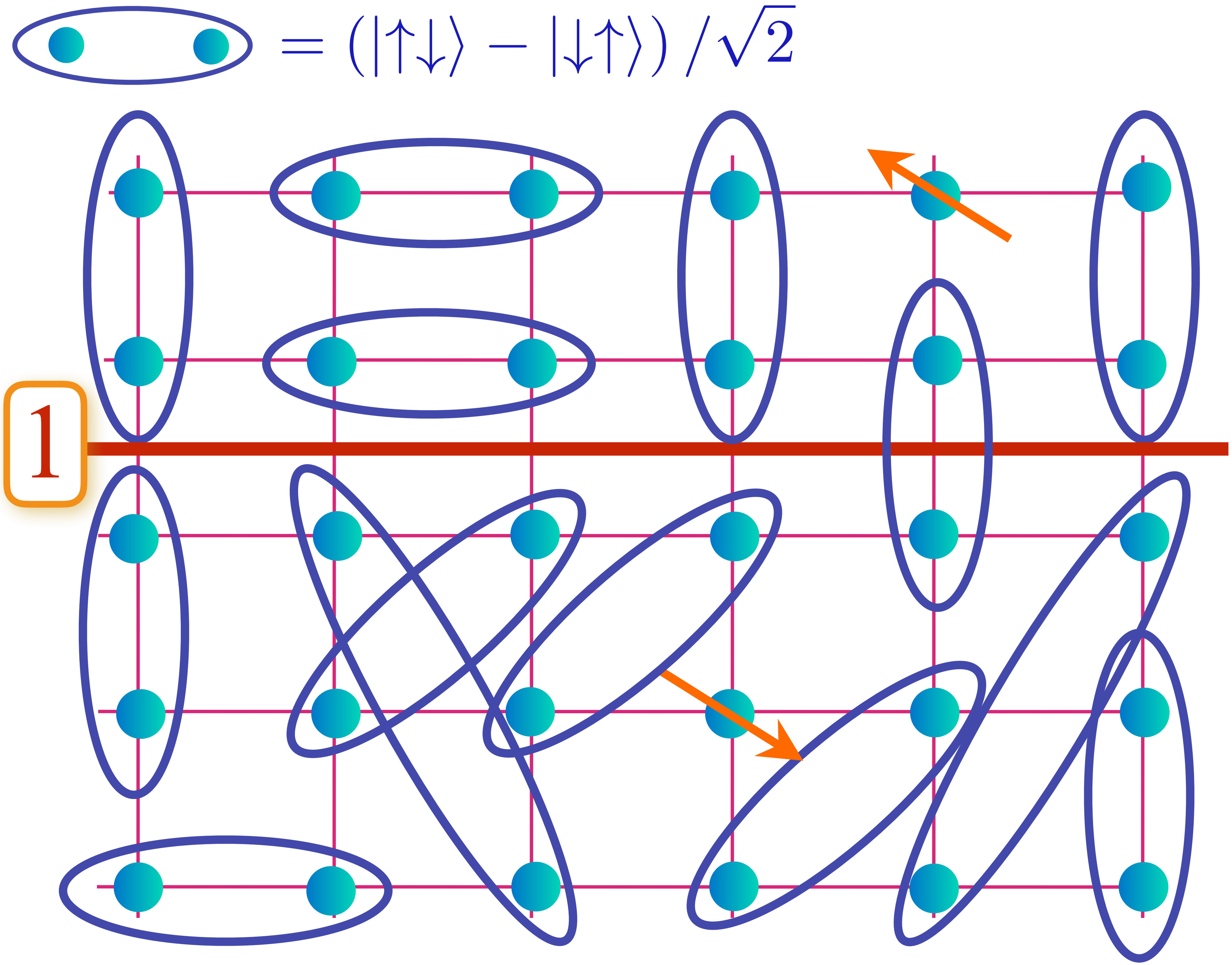
Place insulator on a torus;

to change dimer number parity across red line, it is necessary to create a pair of unpaired spins and move them around the sample.

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

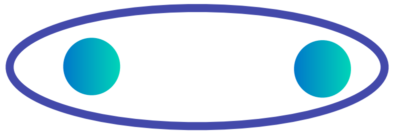


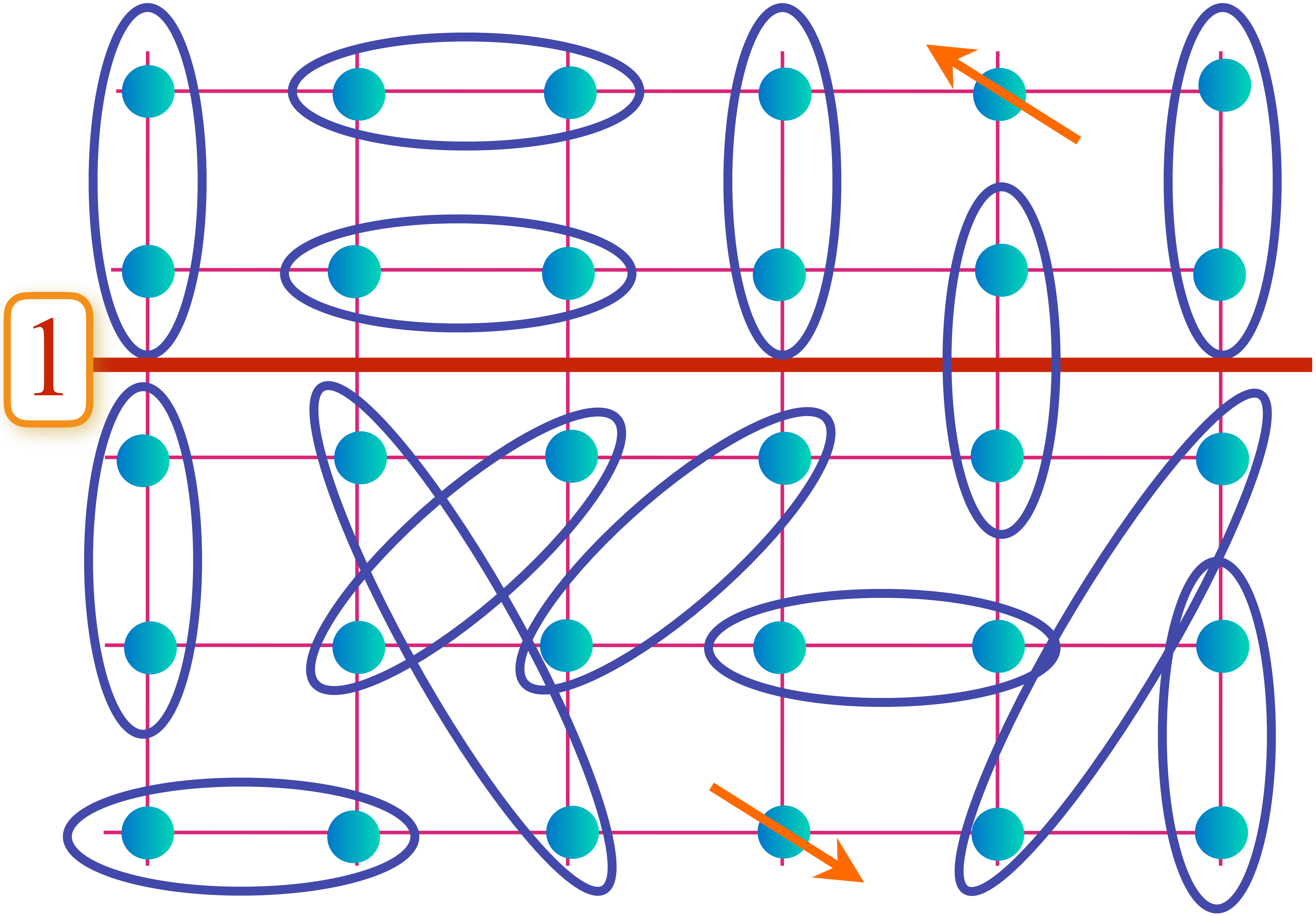
Place insulator on a torus;

to change dimer number parity across red line, it is necessary to create a pair of unpaired spins and move them around the sample.

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

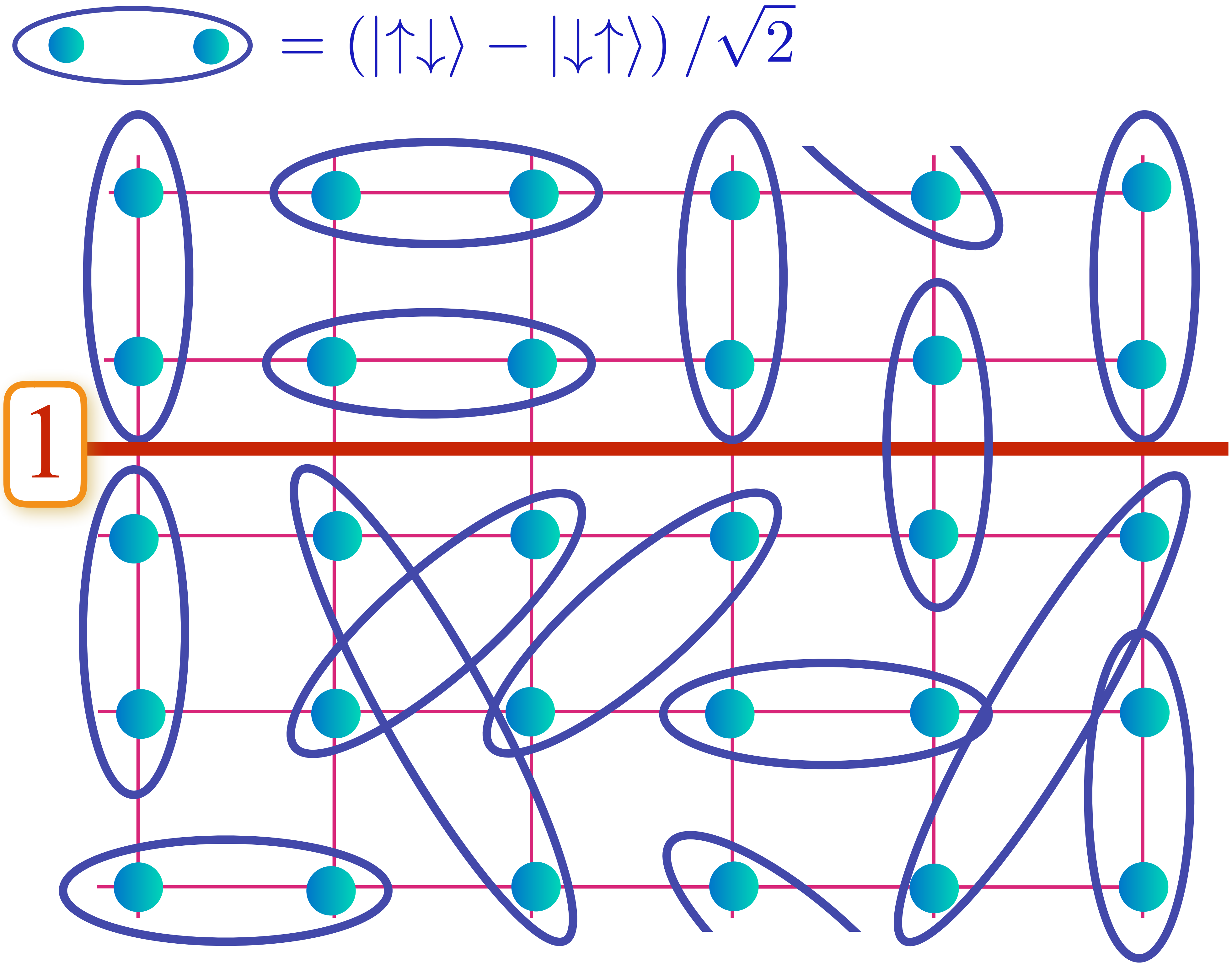


Place insulator on a torus;

to change dimer number parity across red line, it is necessary to create a pair of unpaired spins and move them around the sample.

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy



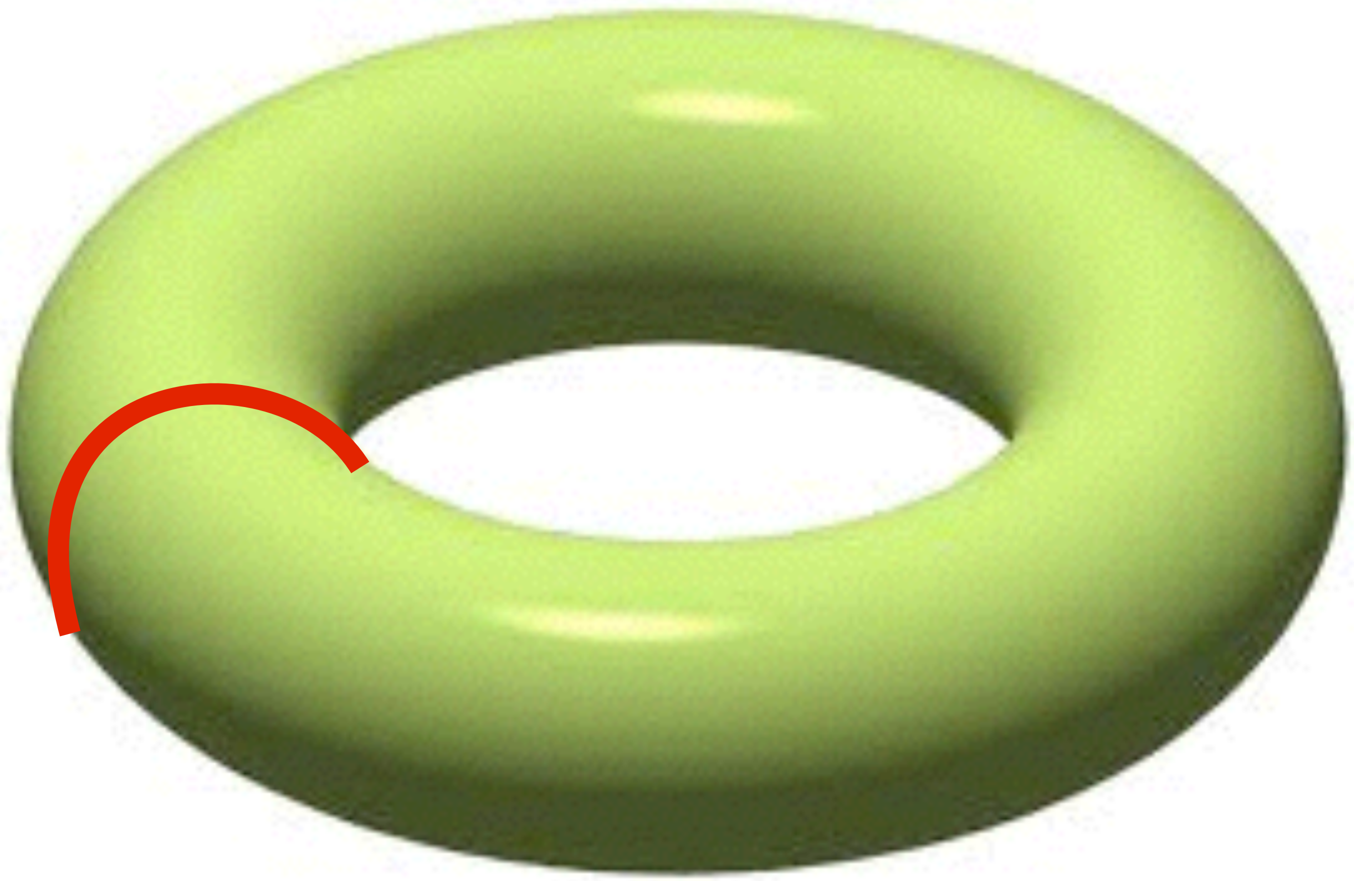
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

Place insulator on a torus;

to change dimer number parity across red line, it is necessary to create a pair of unpaired spins and move them around the sample.

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy

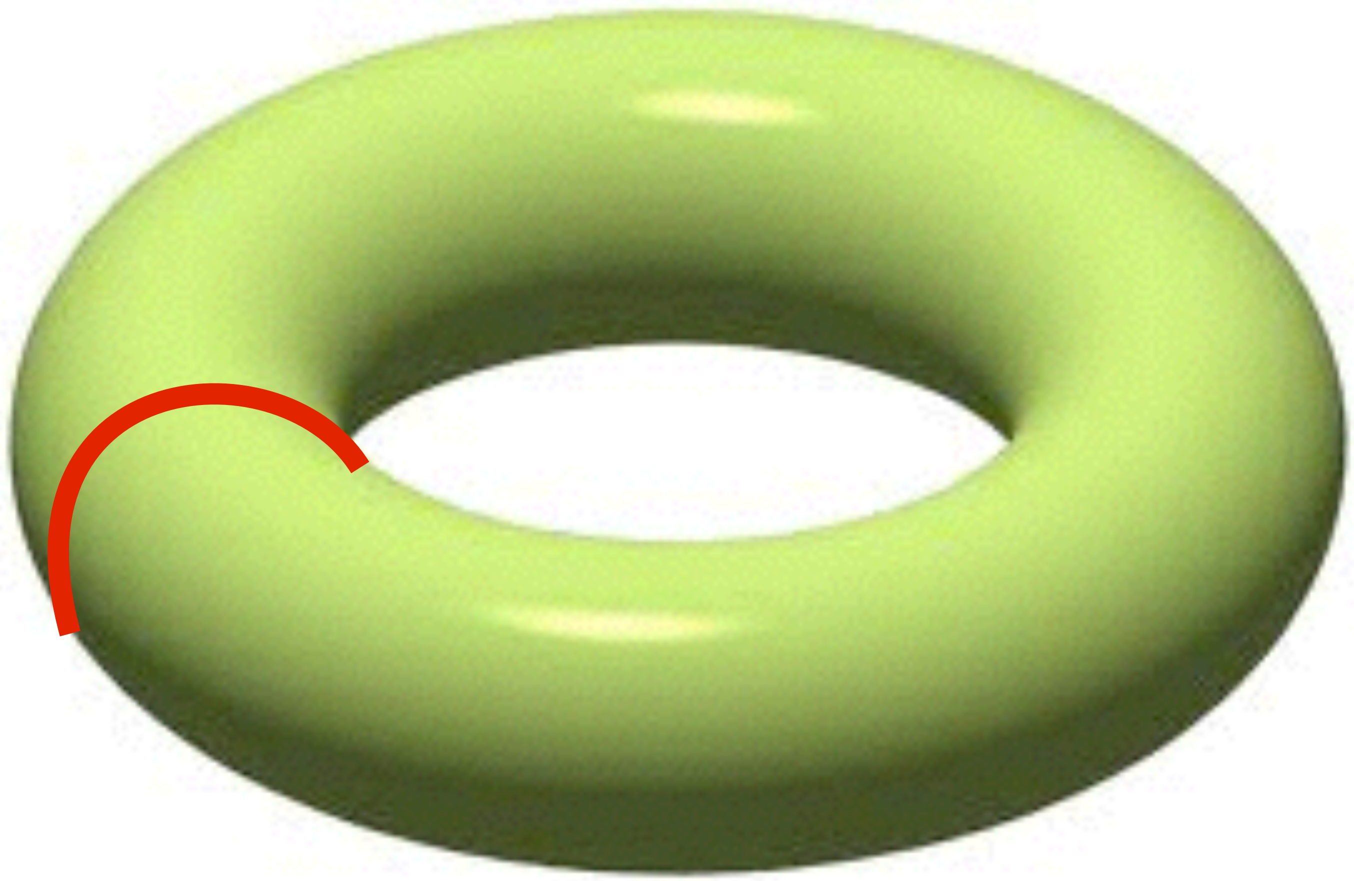


Place insulator on a torus;

The sensitivity of the degeneracy to the global topology indicates long-range quantum entanglement

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

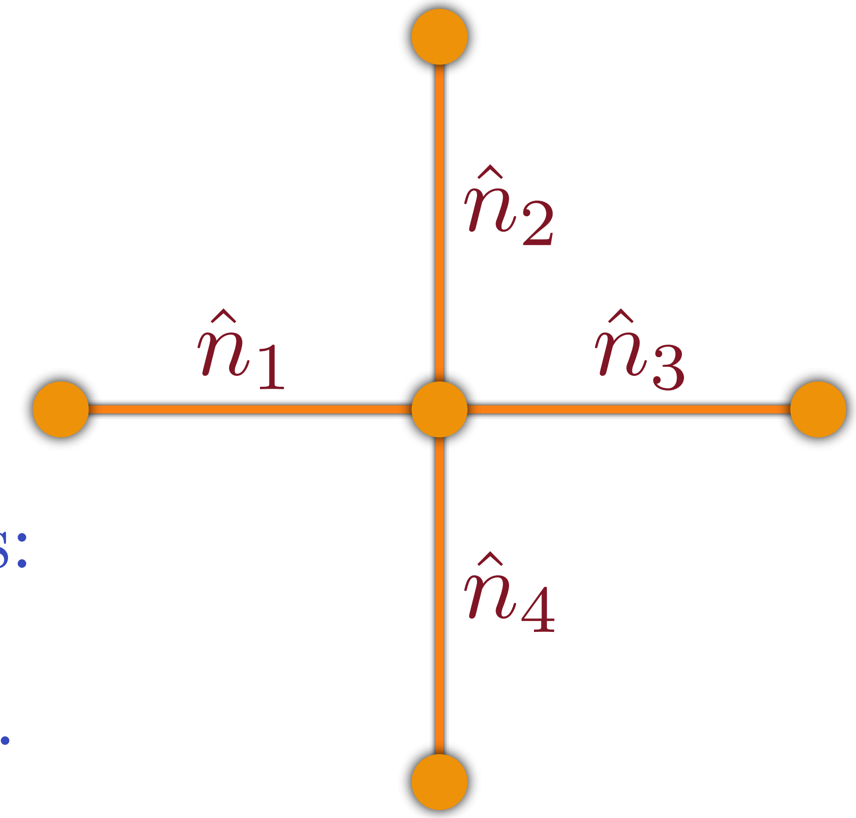
Ground state degeneracy



Place insulator on a torus;
The degenerate states are conjugate to the flux of an emergent gauge field piercing the cycles of the torus

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Emergent gauge fields



Local constraint on dimer number operators:

$$\hat{n}_1 + \hat{n}_2 + \hat{n}_3 + \hat{n}_4 = 1.$$

Identify dimer number with an 'electric' field, $\hat{E}_{i\alpha} = (-1)^{i_x + i_y}\, \hat{n}_{i\alpha}$, $(\alpha = x, y)$; the constraint becomes 'Gauss's Law':

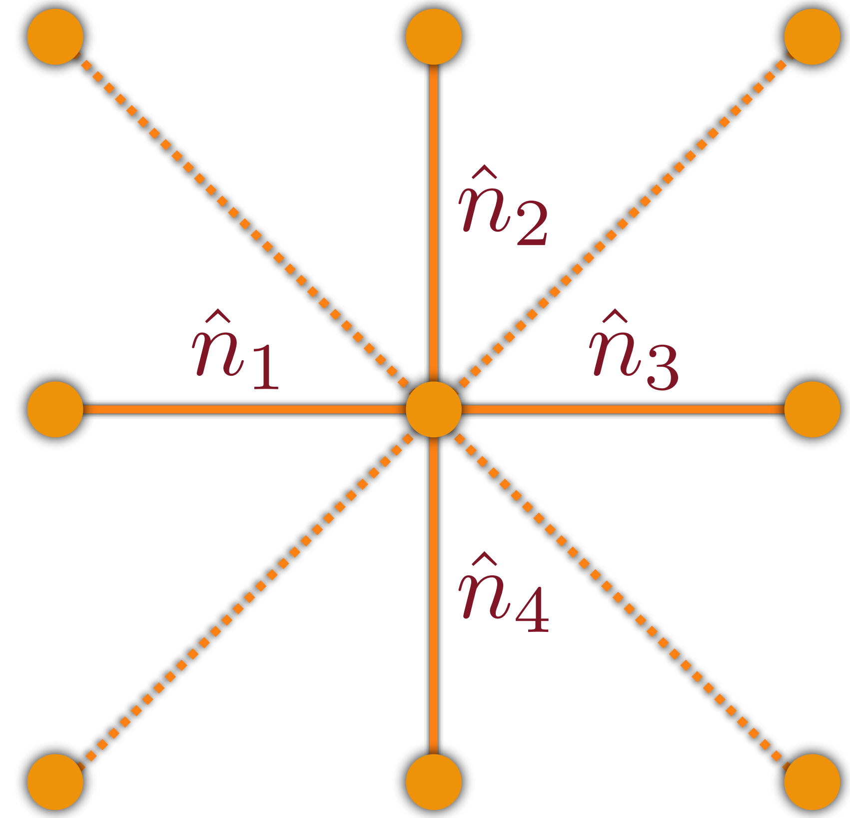
$$\Delta_\alpha \hat{E}_{i\alpha} = (-1)^{i_x + i_y}.$$

The theory of the dimers is *compact* U(1) quantum electrodynamics in the presence of static background charges. The *compact* theory allows the analog of Dirac's magnetic monopoles as tunneling events/excitations.

G. Baskaran and P. W. Anderson, Phys. Rev. B **37**, 580(R) (1988)

E. Fradkin and S. A. Kivelson, Mod. Phys. Lett. B **4**, 225 (1990)

Emergent gauge fields

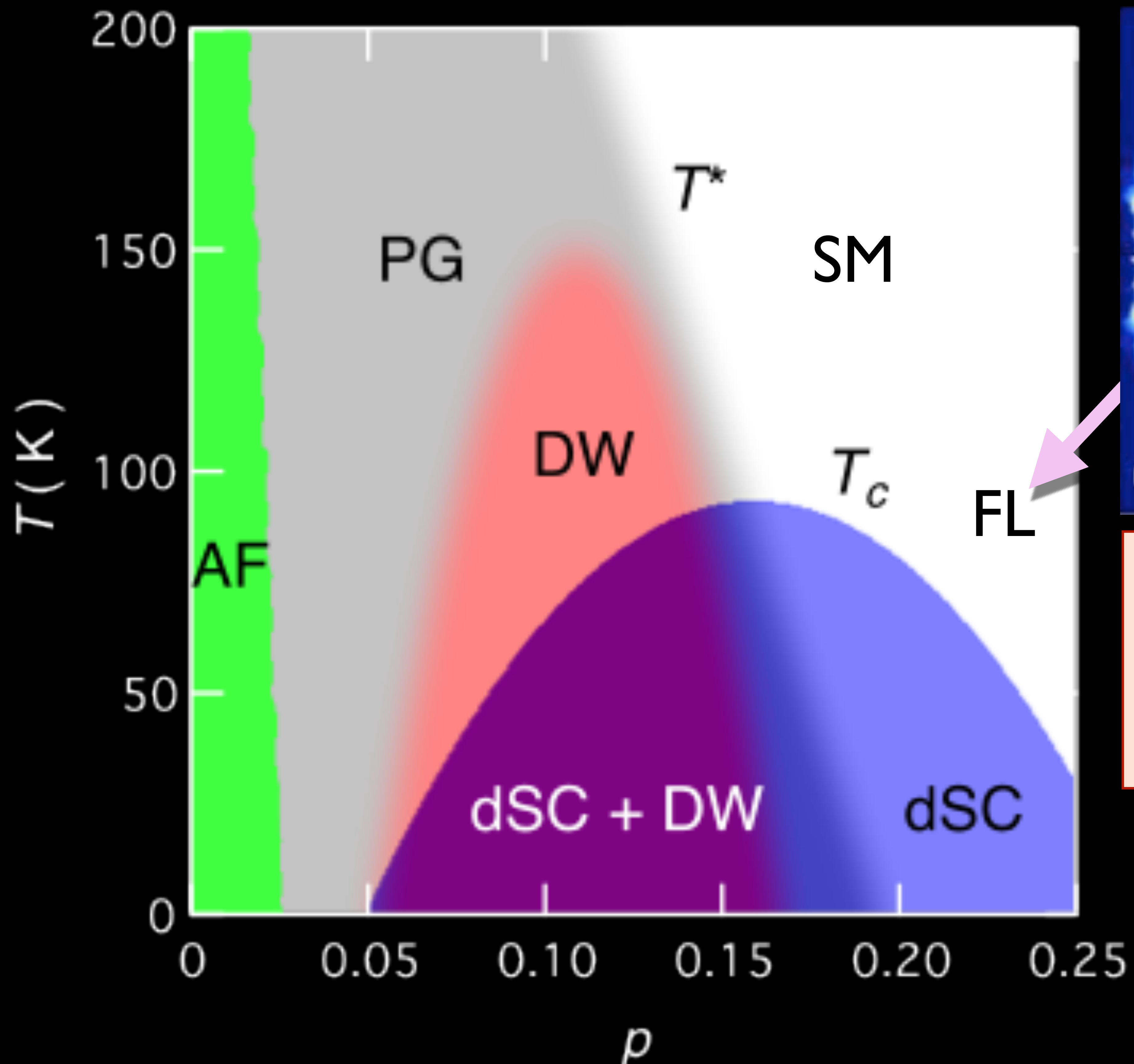


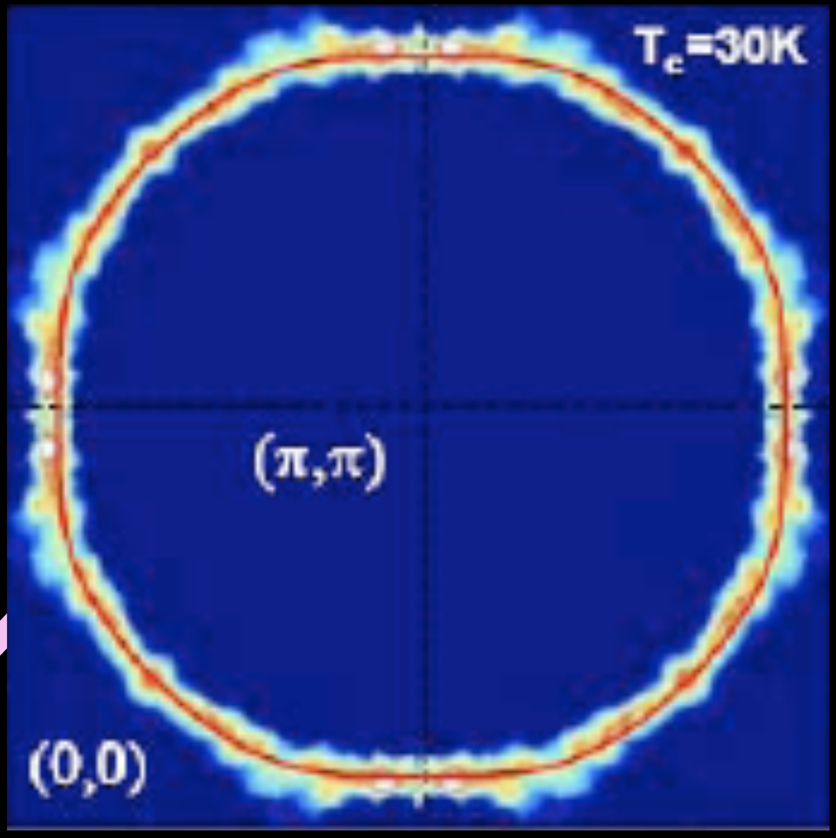
Including dimers connecting the same sublattice leads to a $\mathbb{Z}_2$ gauge theory in the presence of Berry phases of static background charges. This has a stable deconfined phase in 2+1 dimensions. By varying parameters it can undergoes a confinement transition to a valence bond solid, described by a frustrated Ising model.

N. Read and S. Sachdev, Phys. Rev. Lett. 66, 1773 (1991); R.A. Jalabert and S. Sachdev, Phys. Rev. B **44**, 686 (1991); X.-G. Wen, Phys. Rev. B 44, 2664 (1991); S. Sachdev and M. Vojta, J. Phys. Soc. Jpn **69**, Supp. B, 1 (1999)

1. Emergent gauge fields and long-range entanglement in insulators

M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)





A conventional metal: the Fermi liquid

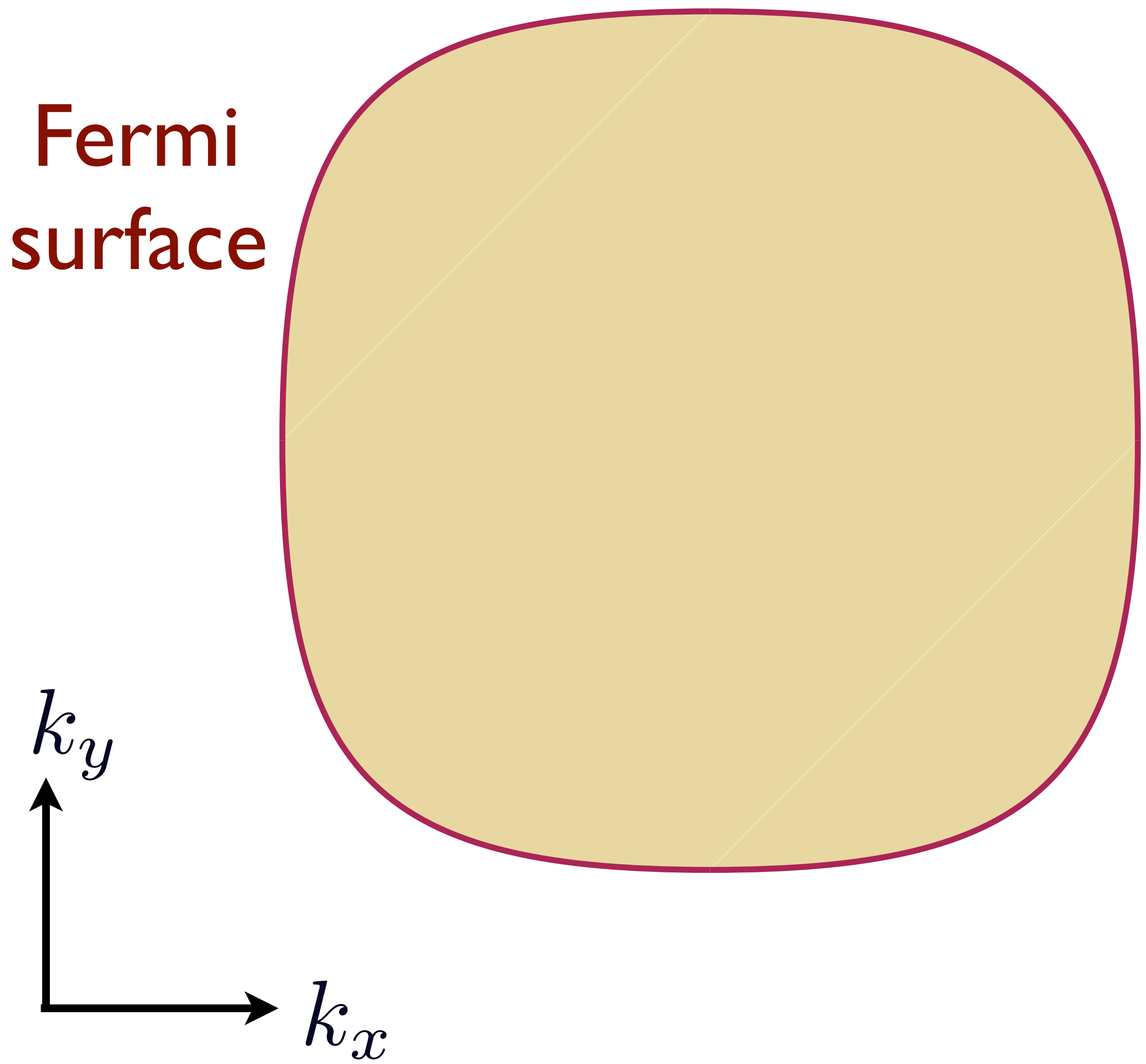
1. Emergent gauge fields and long-range entanglement in insulators

2. Theory of ordinary metals: Fermi liquids (FL)

   (a) Quasiparticles

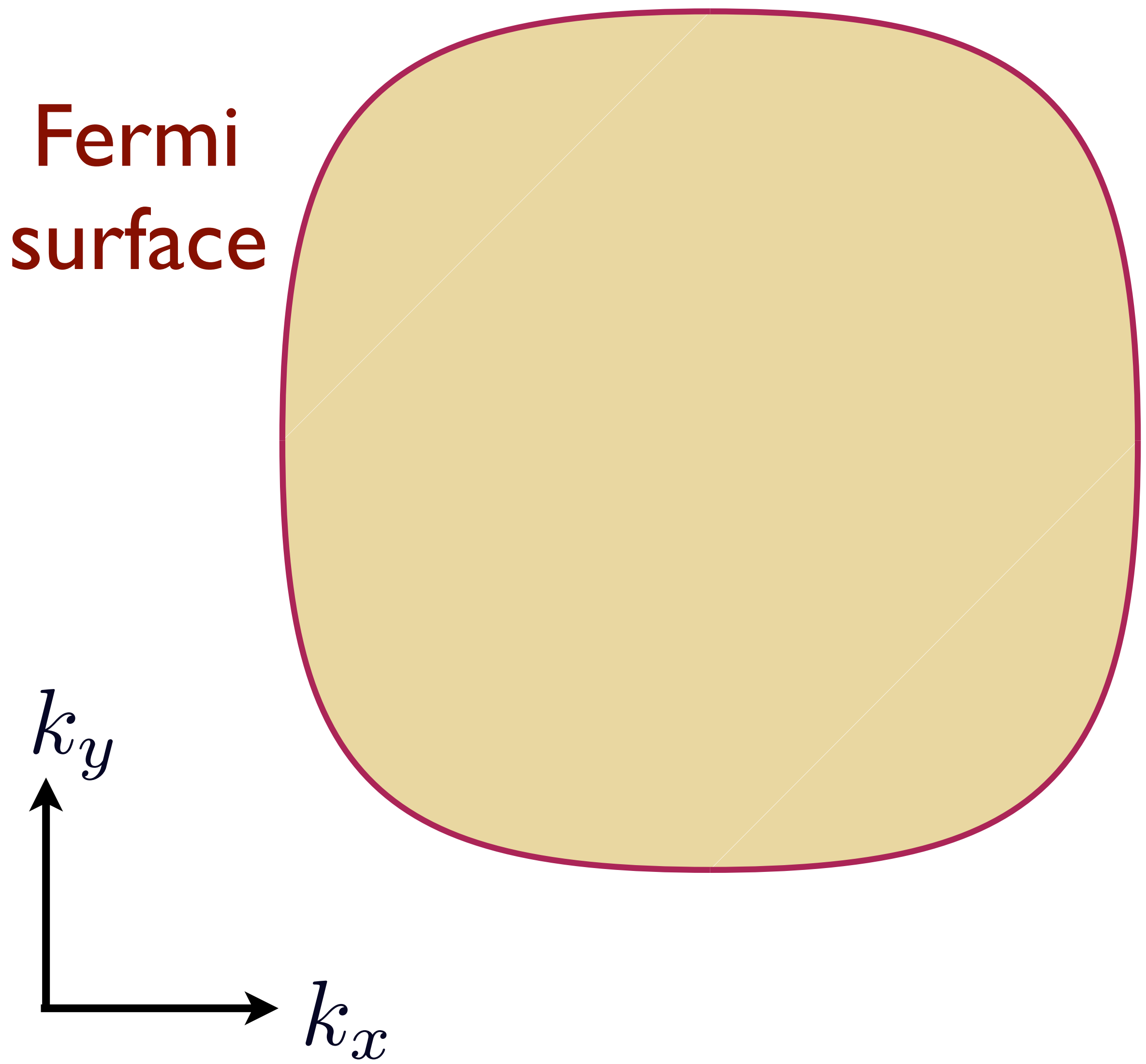
   (b) Luttinger theorem for volume enclosed by Fermi surface

Ordinary metals: the Fermi liquid



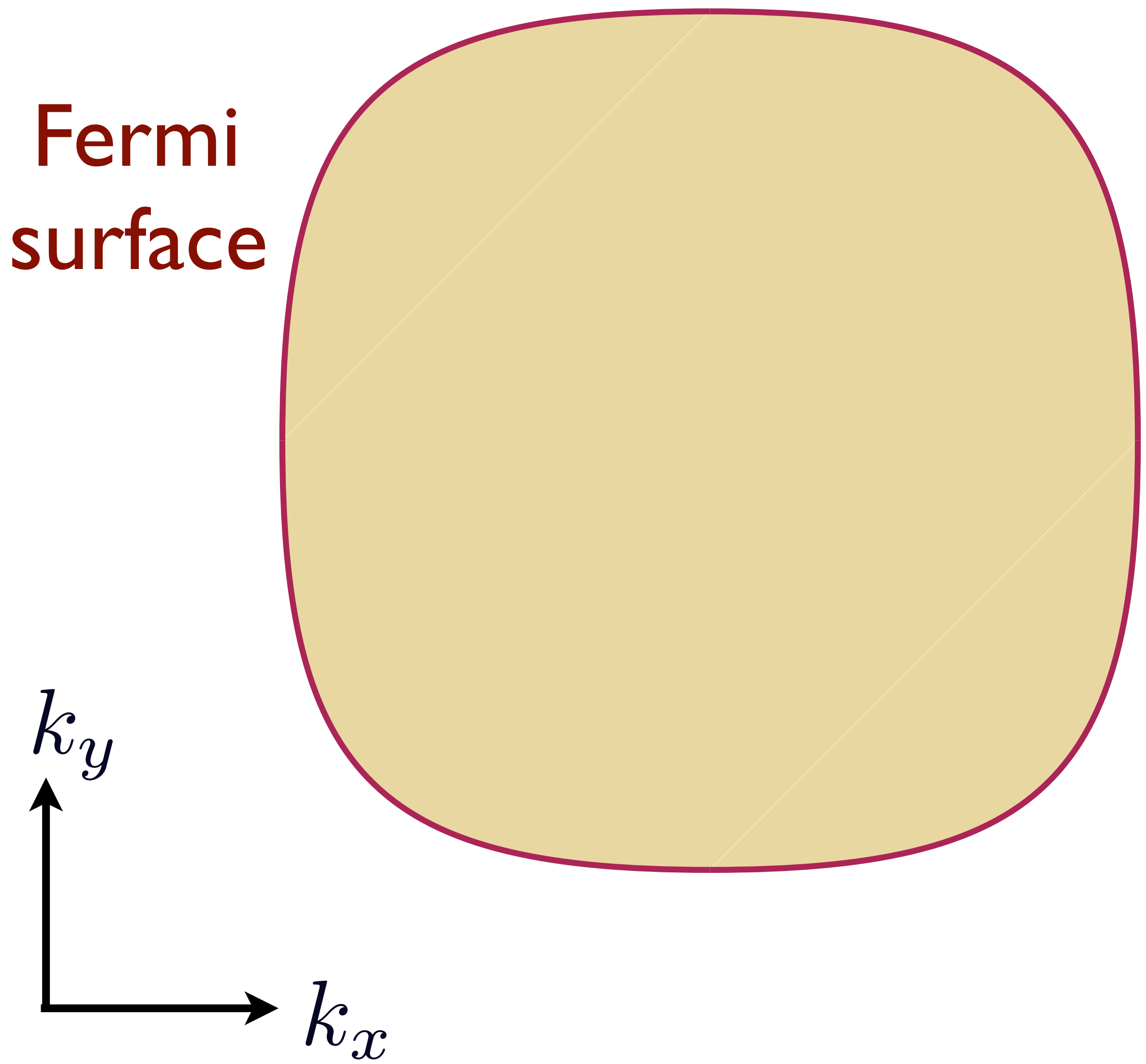
- Fermi surface separates empty and occupied states in momentum space.

Ordinary metals: the Fermi liquid

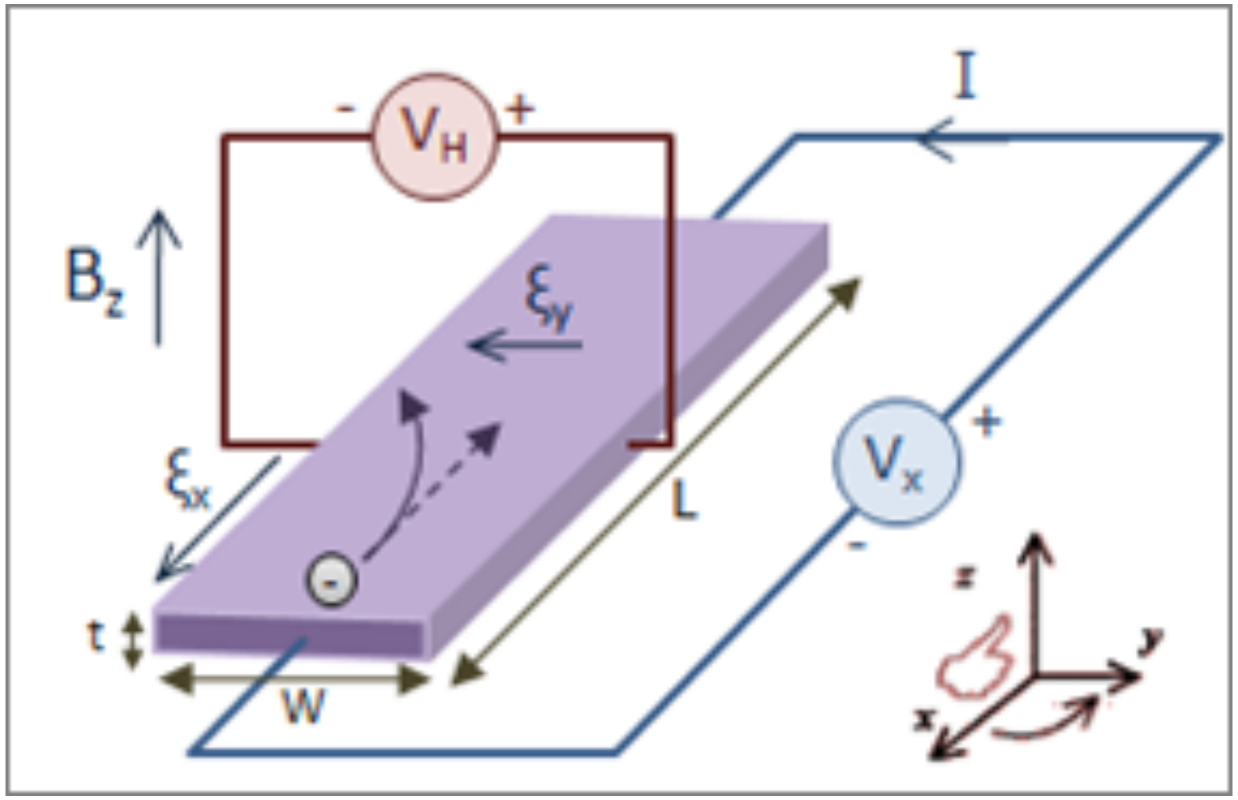


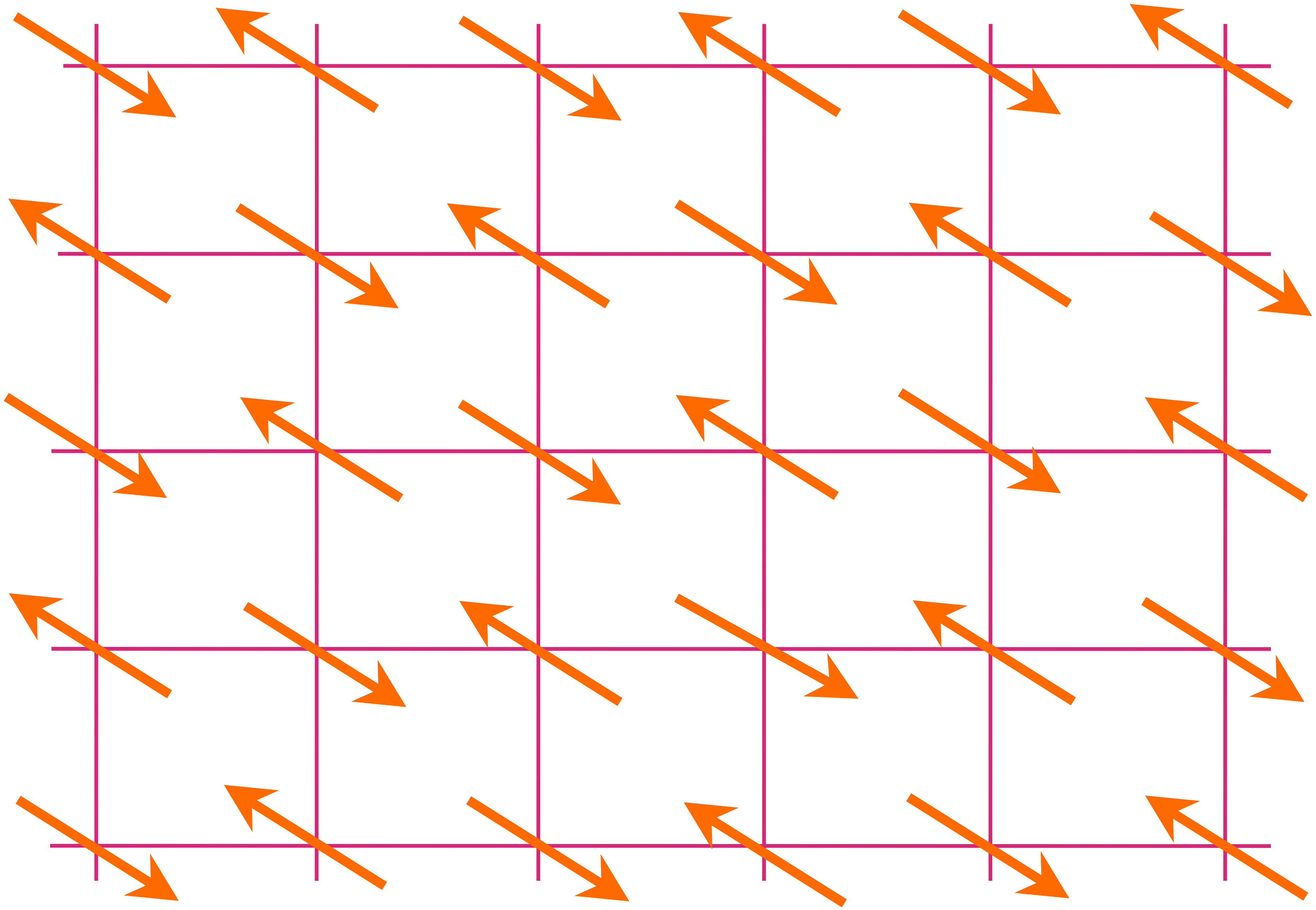
- Fermi surface separates empty and occupied states in momentum space.
- *Luttinger Theorem*: volume (area) enclosed by Fermi surface = the electron density.

Ordinary metals: the Fermi liquid

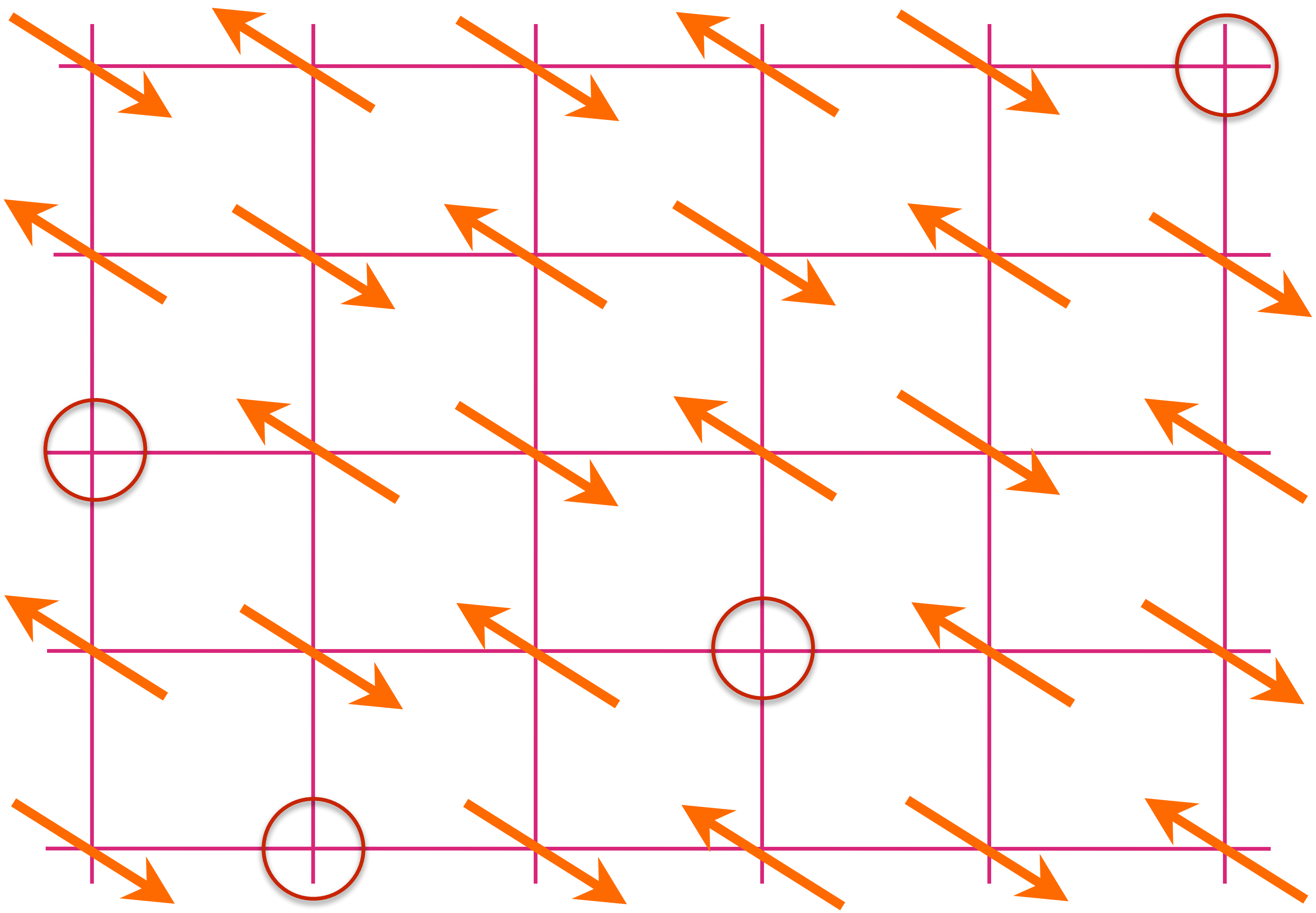


- Fermi surface separates empty and occupied states in momentum space.
- *Luttinger Theorem*: volume (area) enclosed by Fermi surface = the electron density.
- Hall co-efficient $R_H = -1/((\text{Fermi volume}) \times e)$.

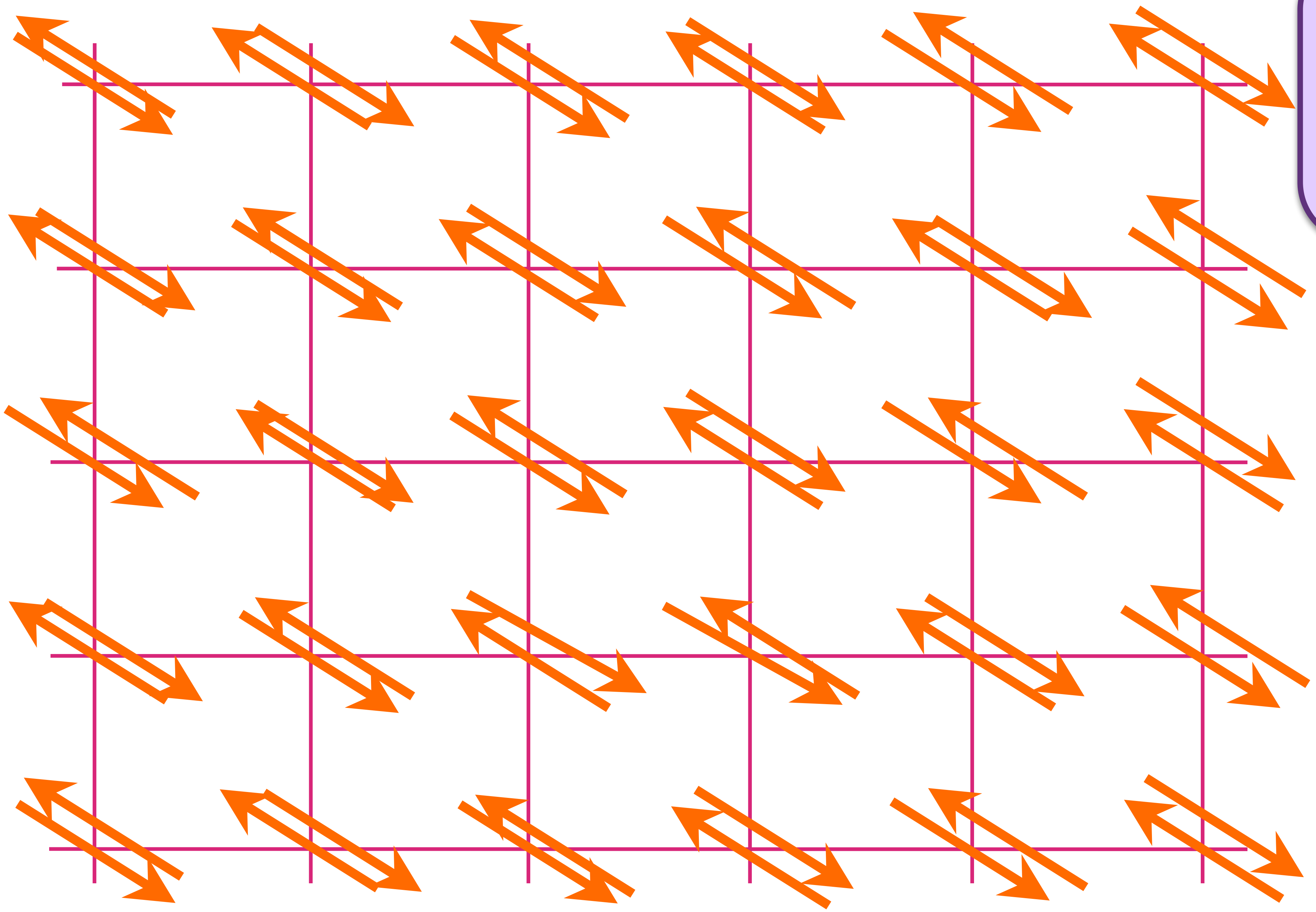




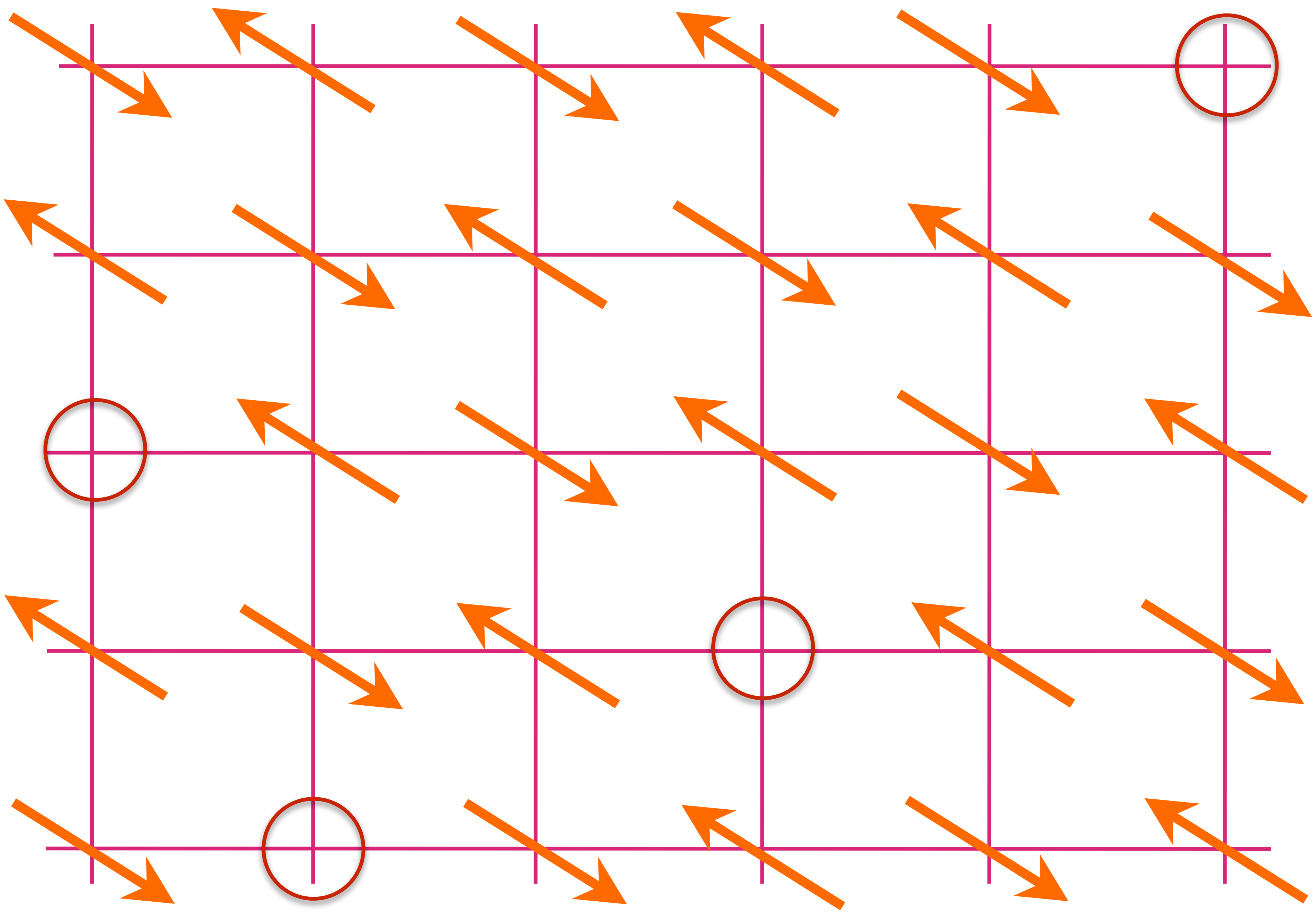
“Undoped” Anti-ferromagnet



Anti-ferromagnet with p holes per square



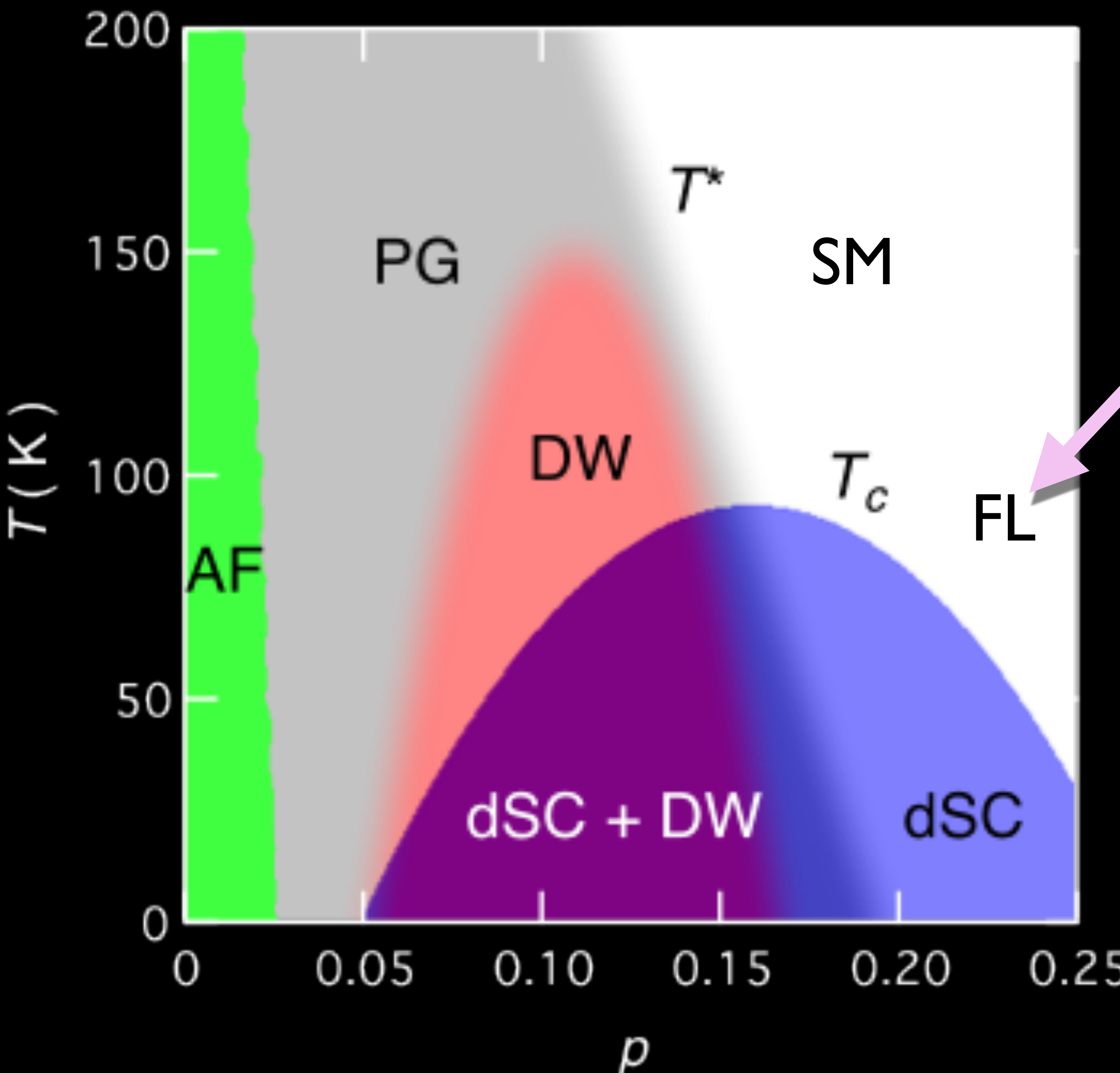
Filled Band

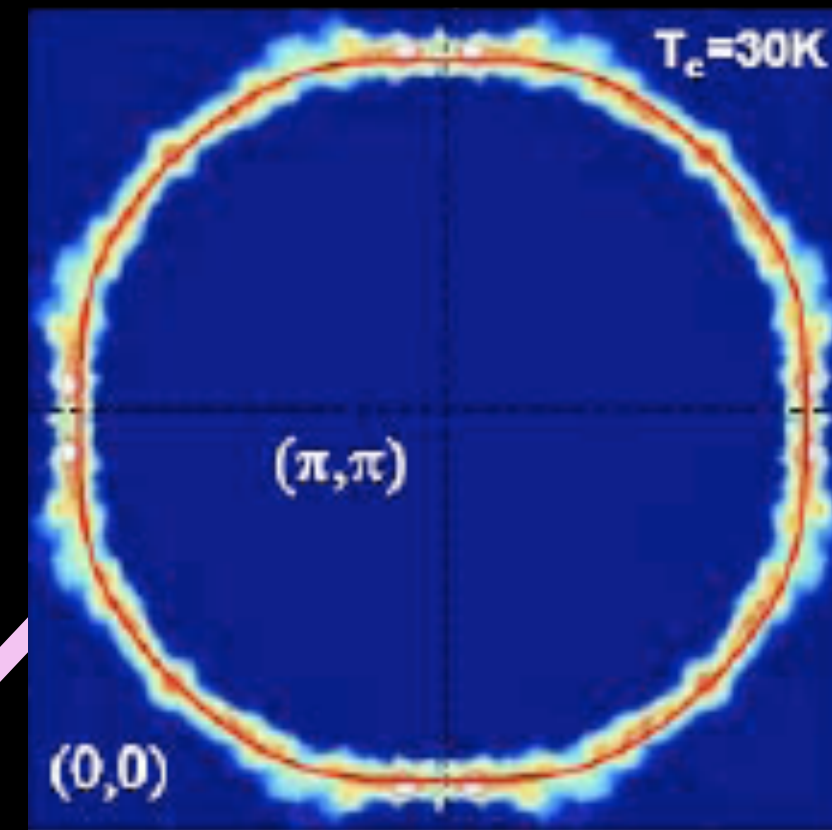


Anti-ferromagnet with p holes per square

But relative to the band insulator, there are $1+p$ holes per square, and so a Fermi liquid has a Fermi surface of size $1+p$

M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)

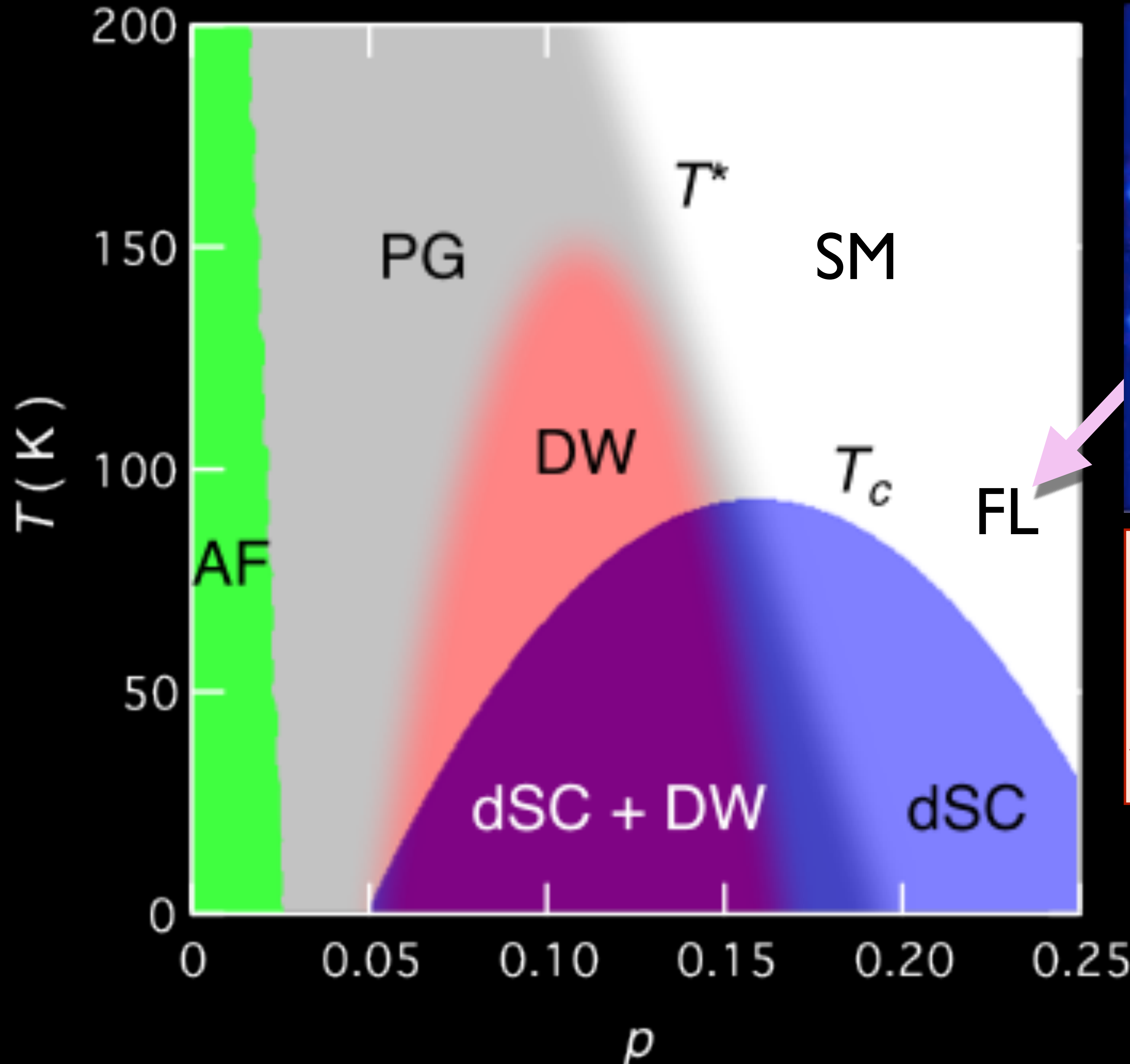


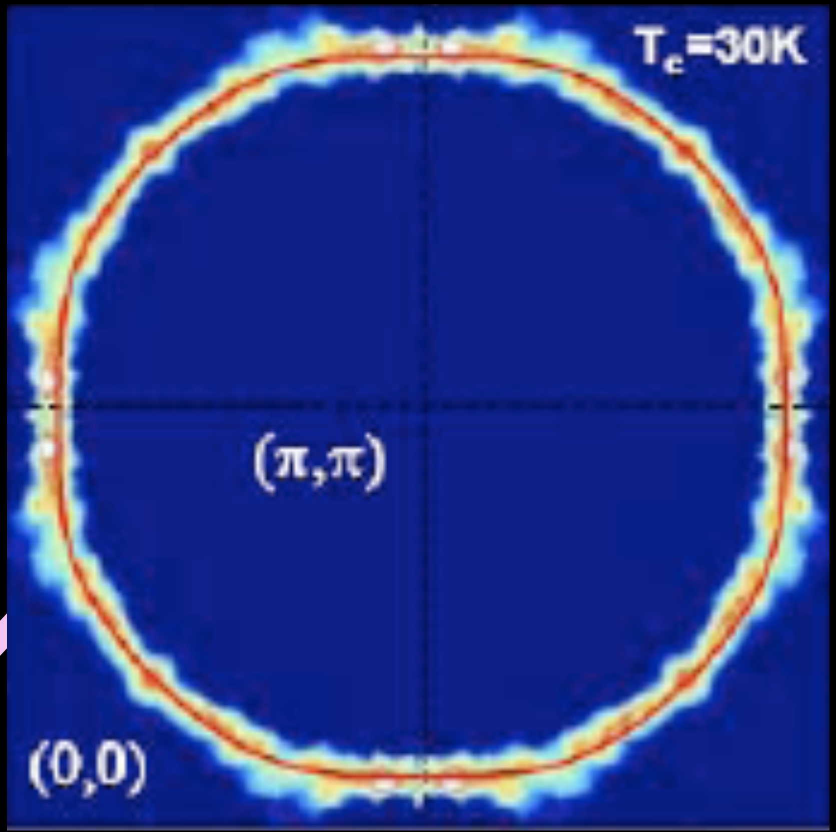


Fermi liquid

Area enclosed by Fermi surface =1+p

M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)



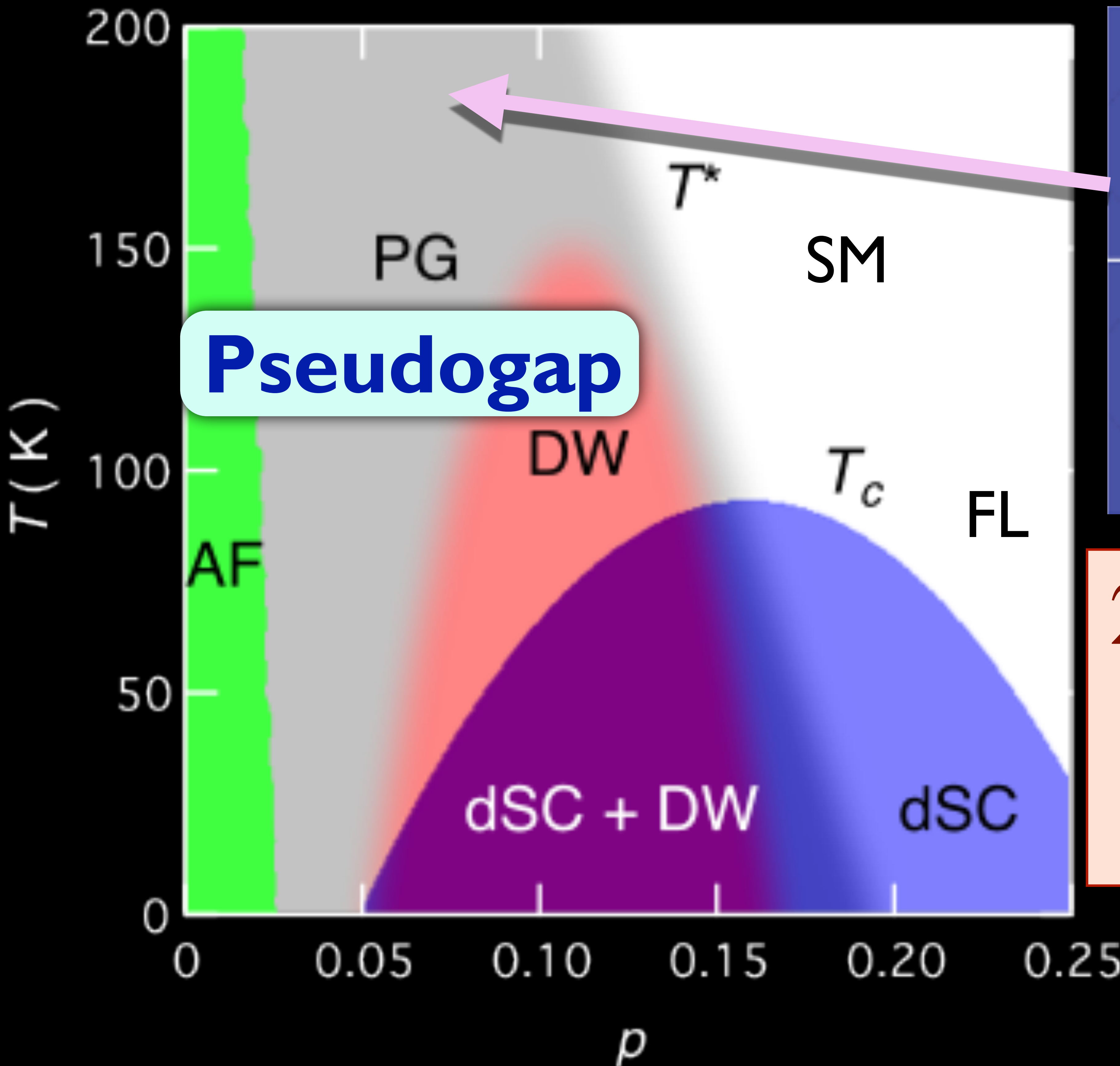


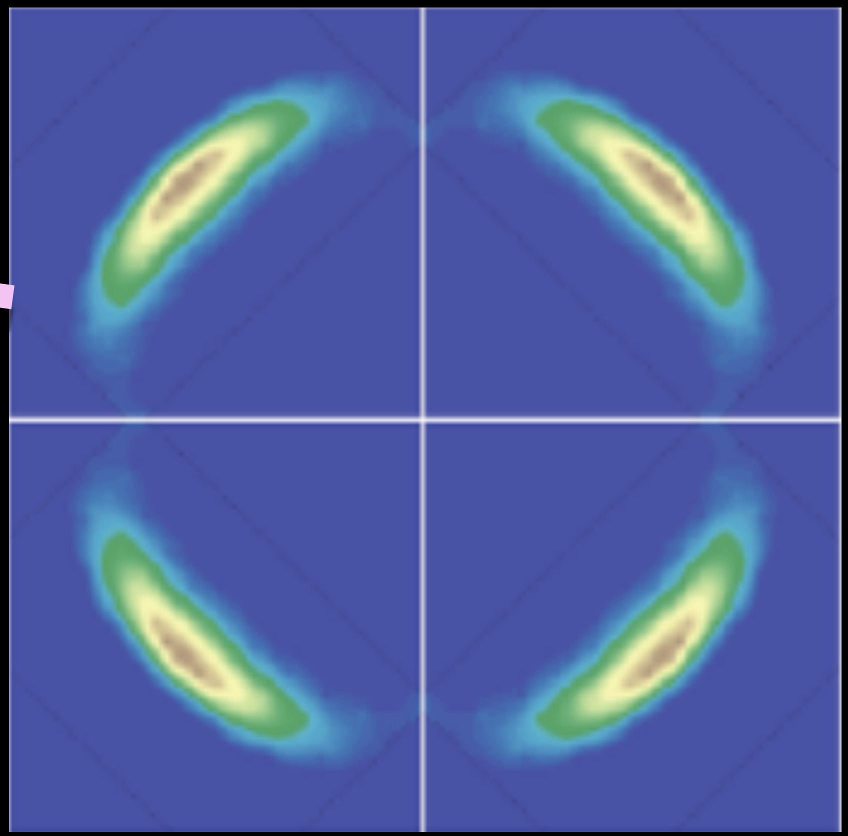
Fermi liquid

Hall co-efficient

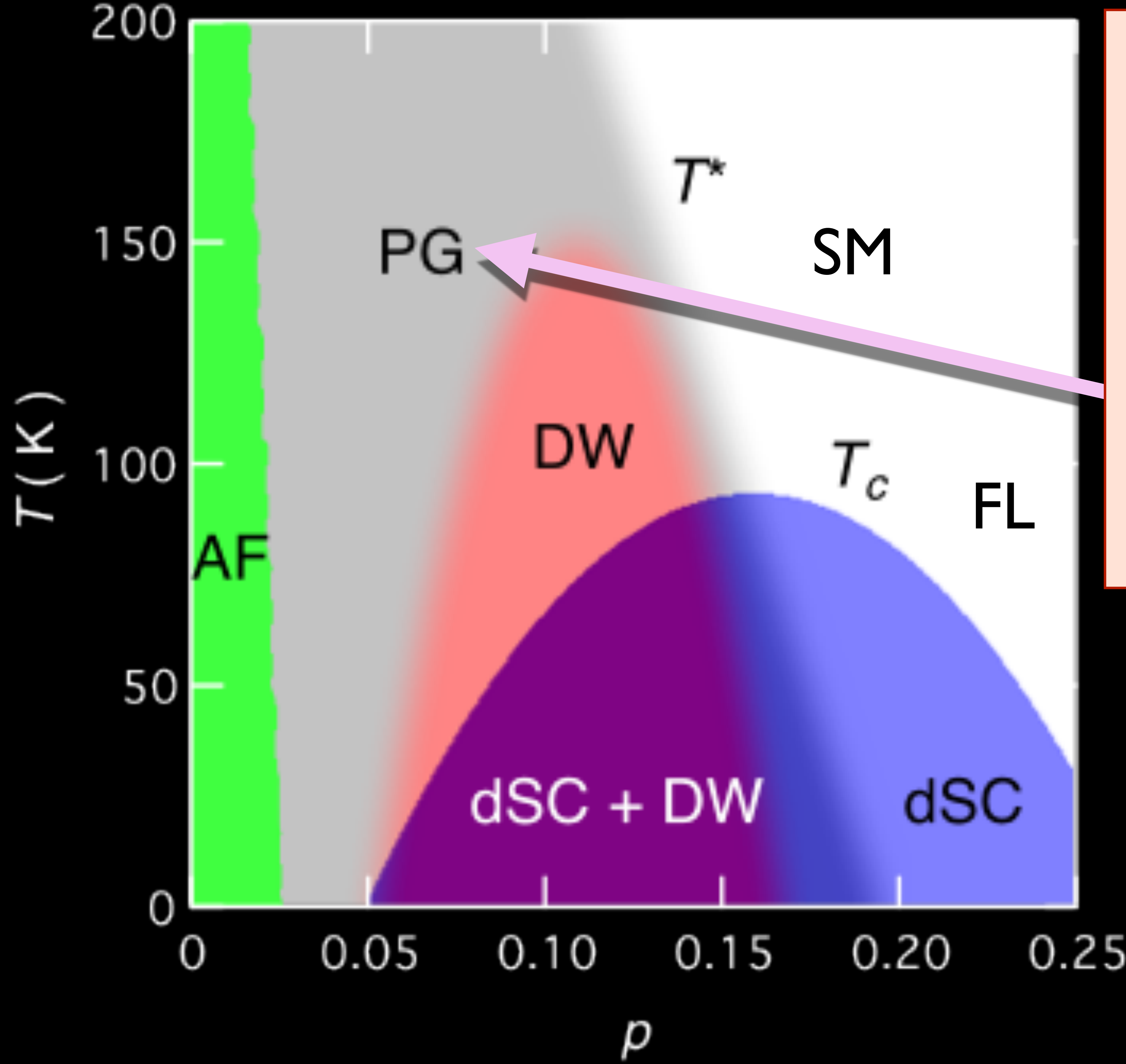
$$R_H = +1/((1+p)e).$$

Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

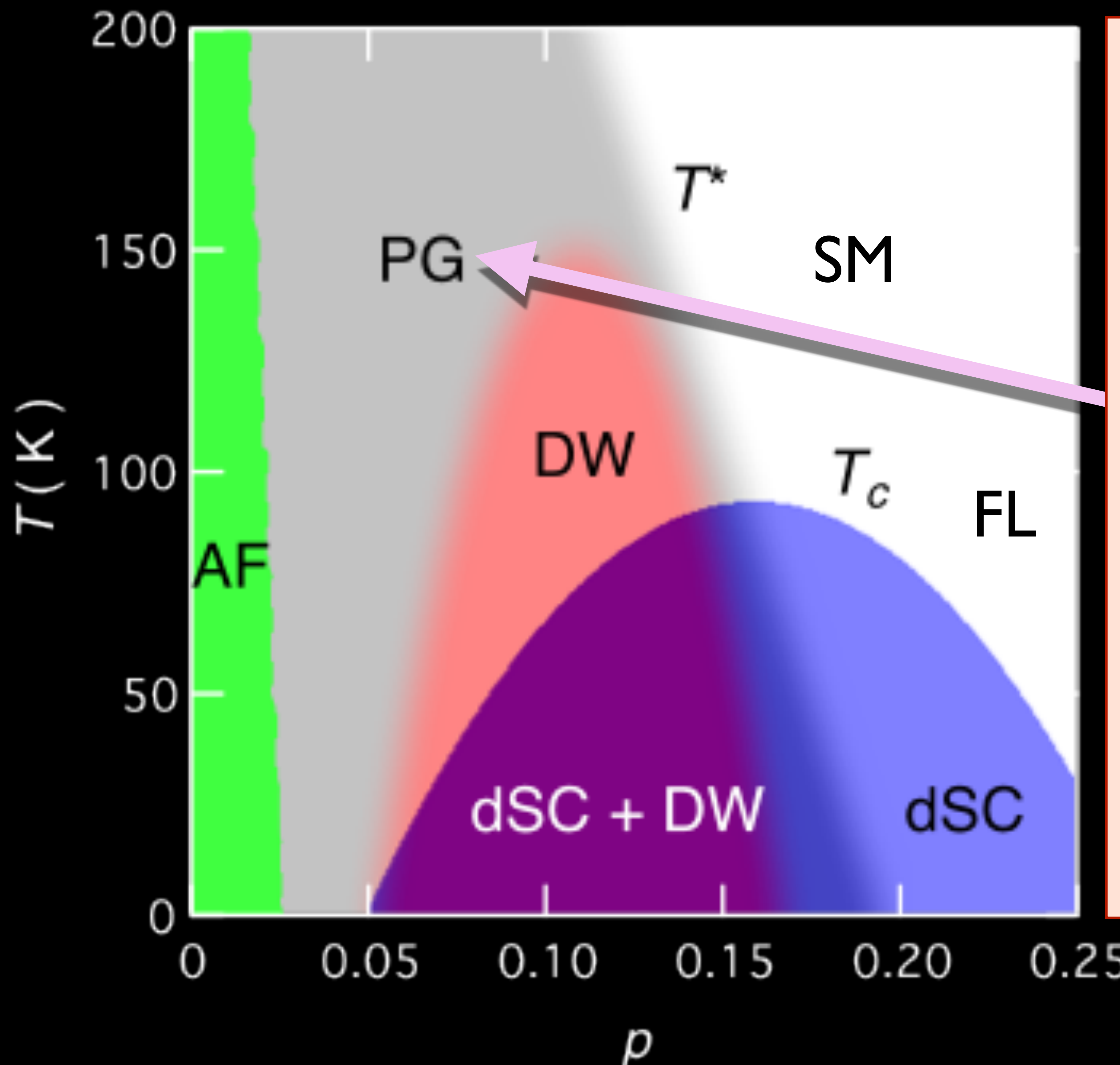




2. Pseudogap metal at low p



The PG regime behaves in many respects like a Fermi liquid, but with a Fermi surface size of p and not $1+p$



The PG regime behaves in many respects like a Fermi liquid, but with a Fermi surface size of p and not $1+p$

.e.g. Hall co-efficient $R_H = +1/(pe)$.

1. Emergent gauge fields and long-range entanglement in insulators

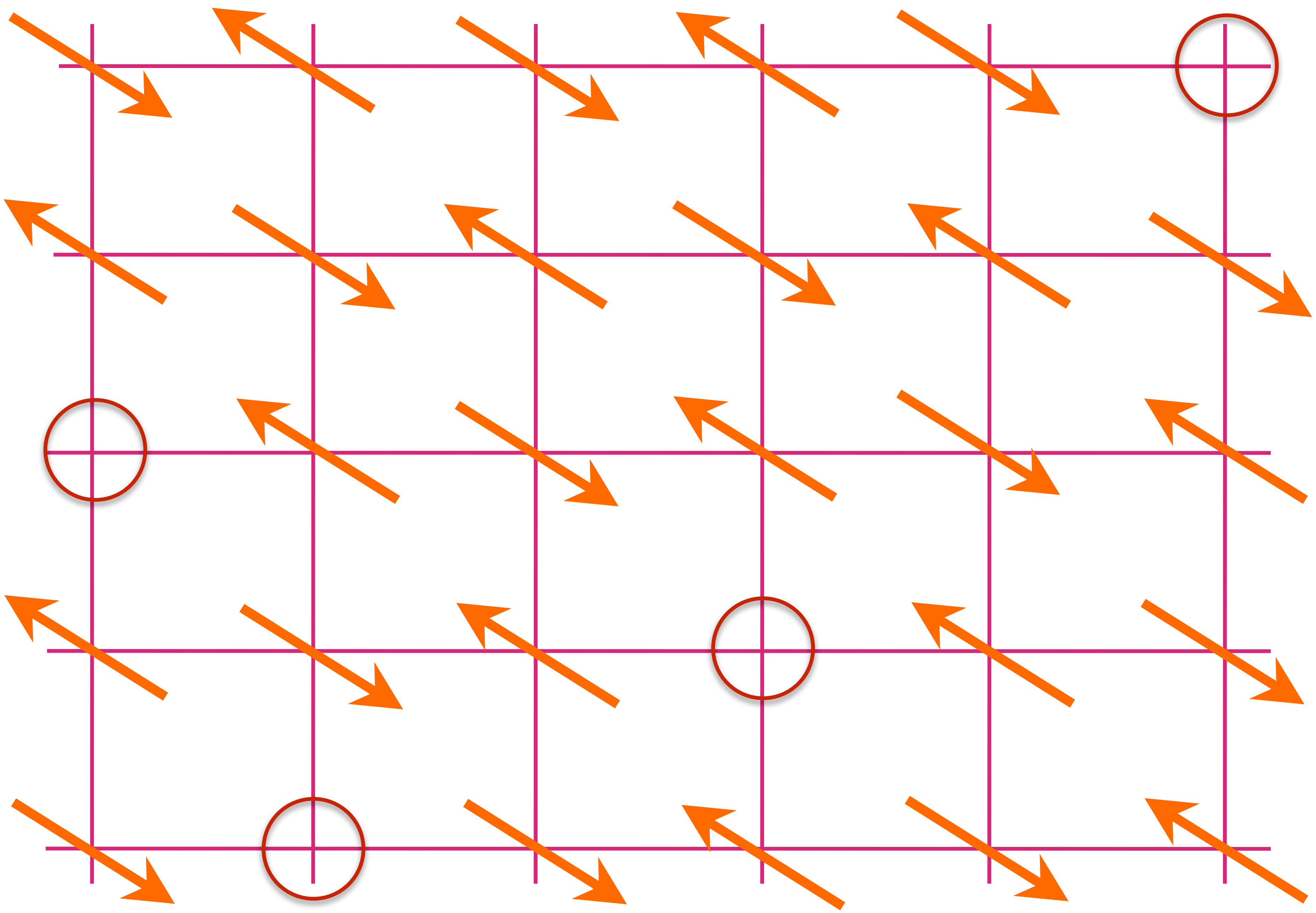
2. Theory of ordinary metals: Fermi liquids (FL)

   (a) Quasiparticles

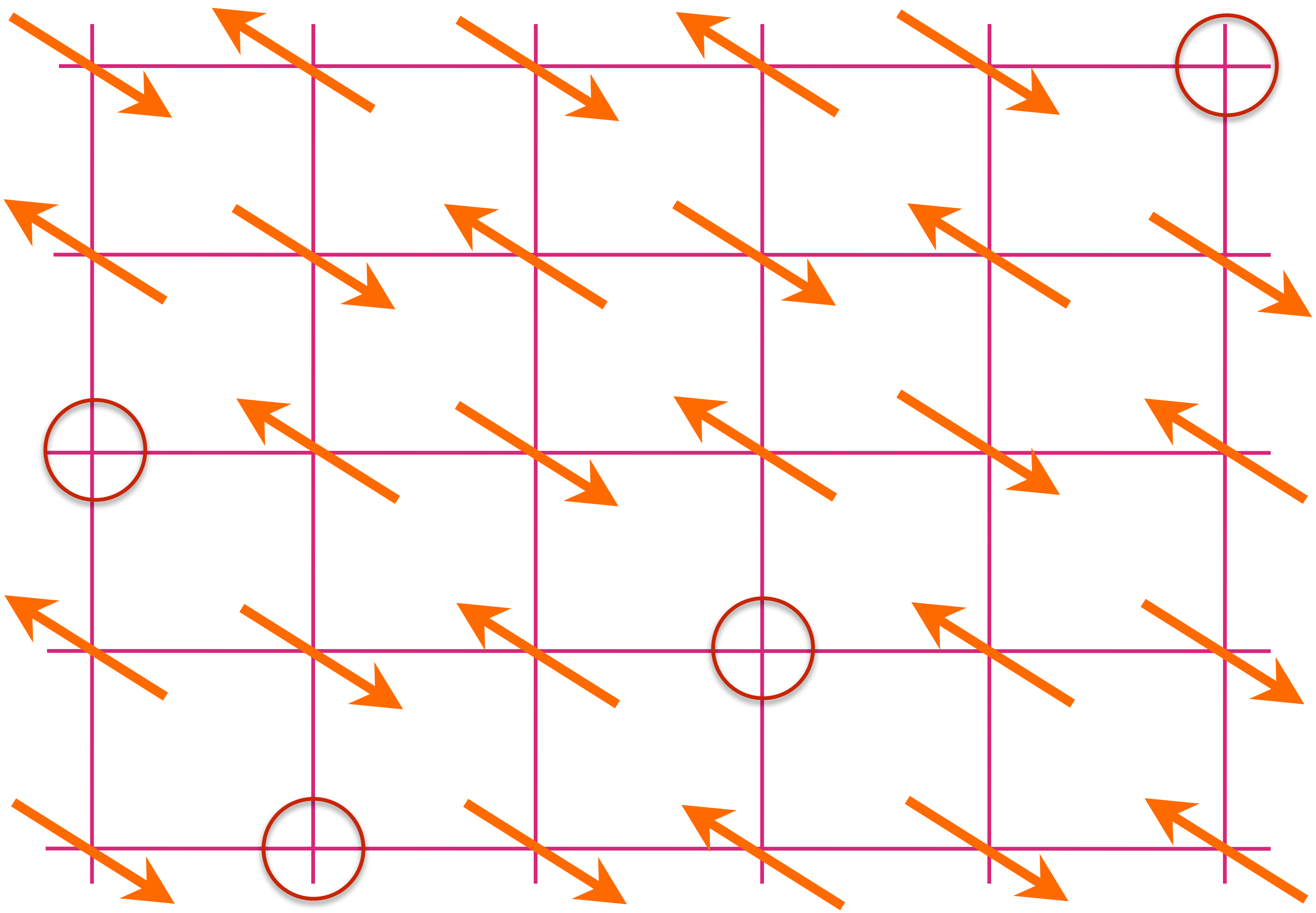
   (b) Luttinger theorem for volume enclosed by Fermi surface

3. The FL* phase:

   Quasiparticles with a non-Luttinger volume, and emergent gauge fields



Anti-ferromagnet with p holes per square

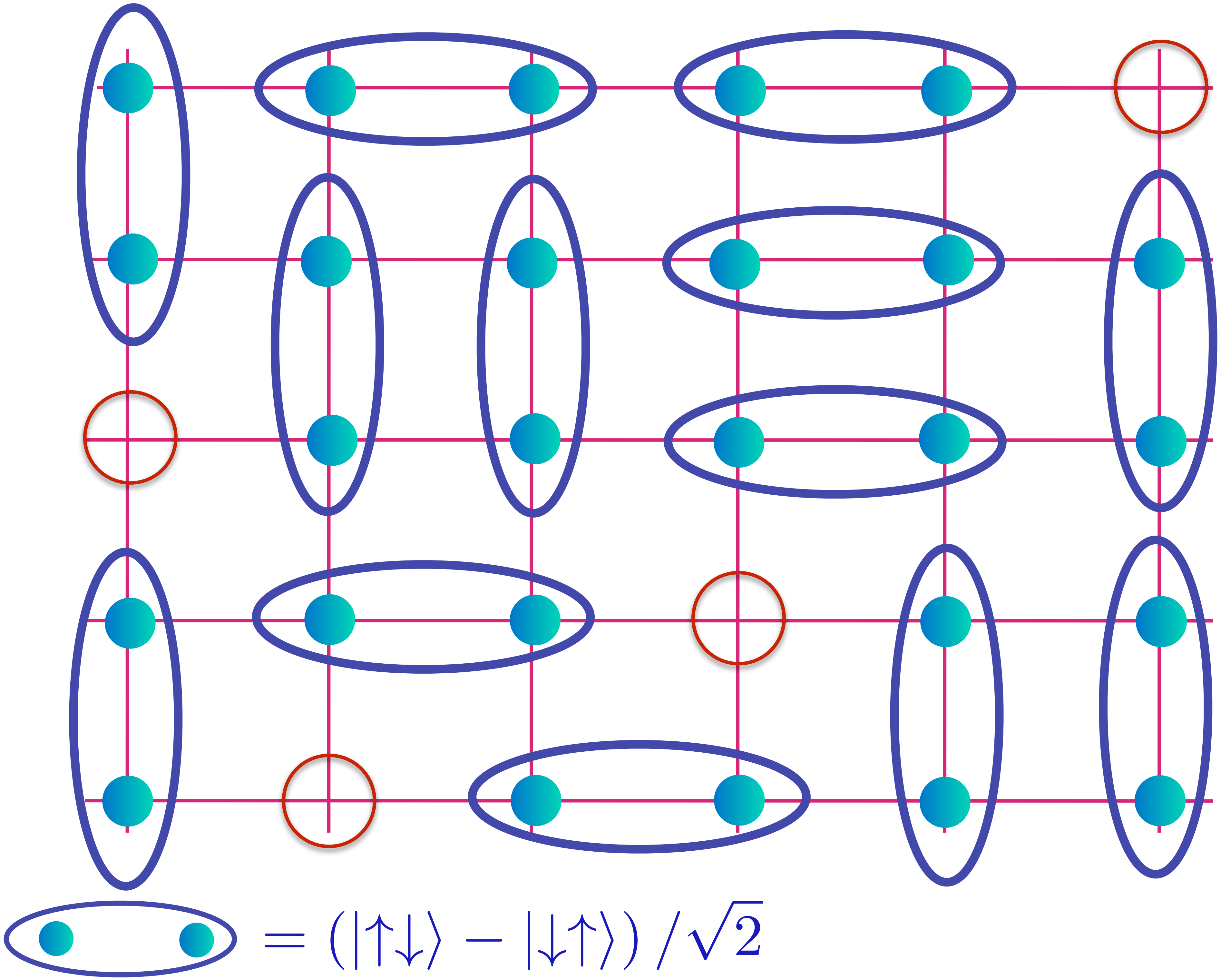


Anti-ferromagnet with p holes per square

Can we get a Fermi surface of size p?
(and full square lattice symmetry)

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)

N. Read and B. Chakraborty, PRB **40**, 7133 (1989)

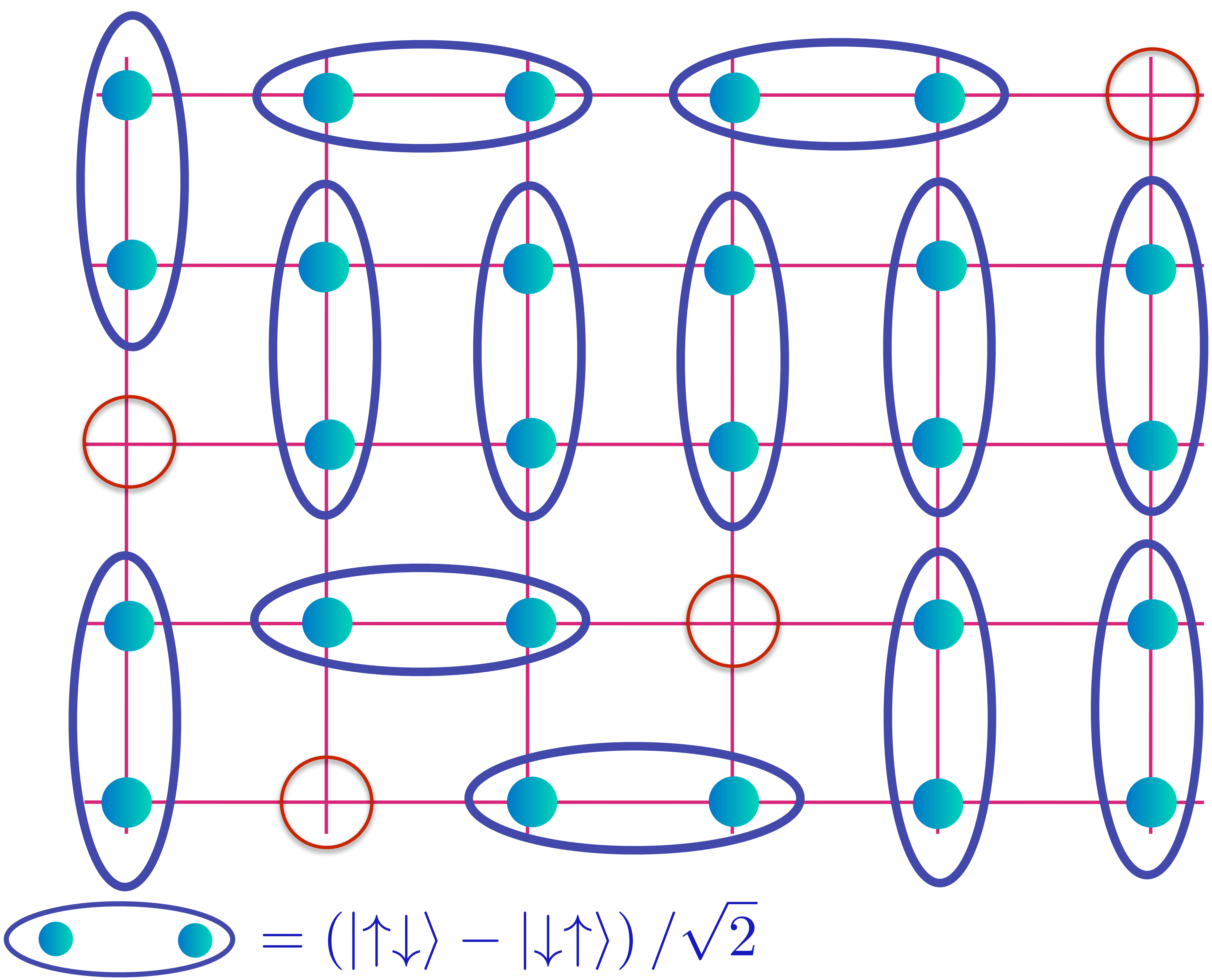


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$

Spin liquid with density *p* of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)

N. Read and B. Chakraborty, PRB **40**, 7133 (1989)

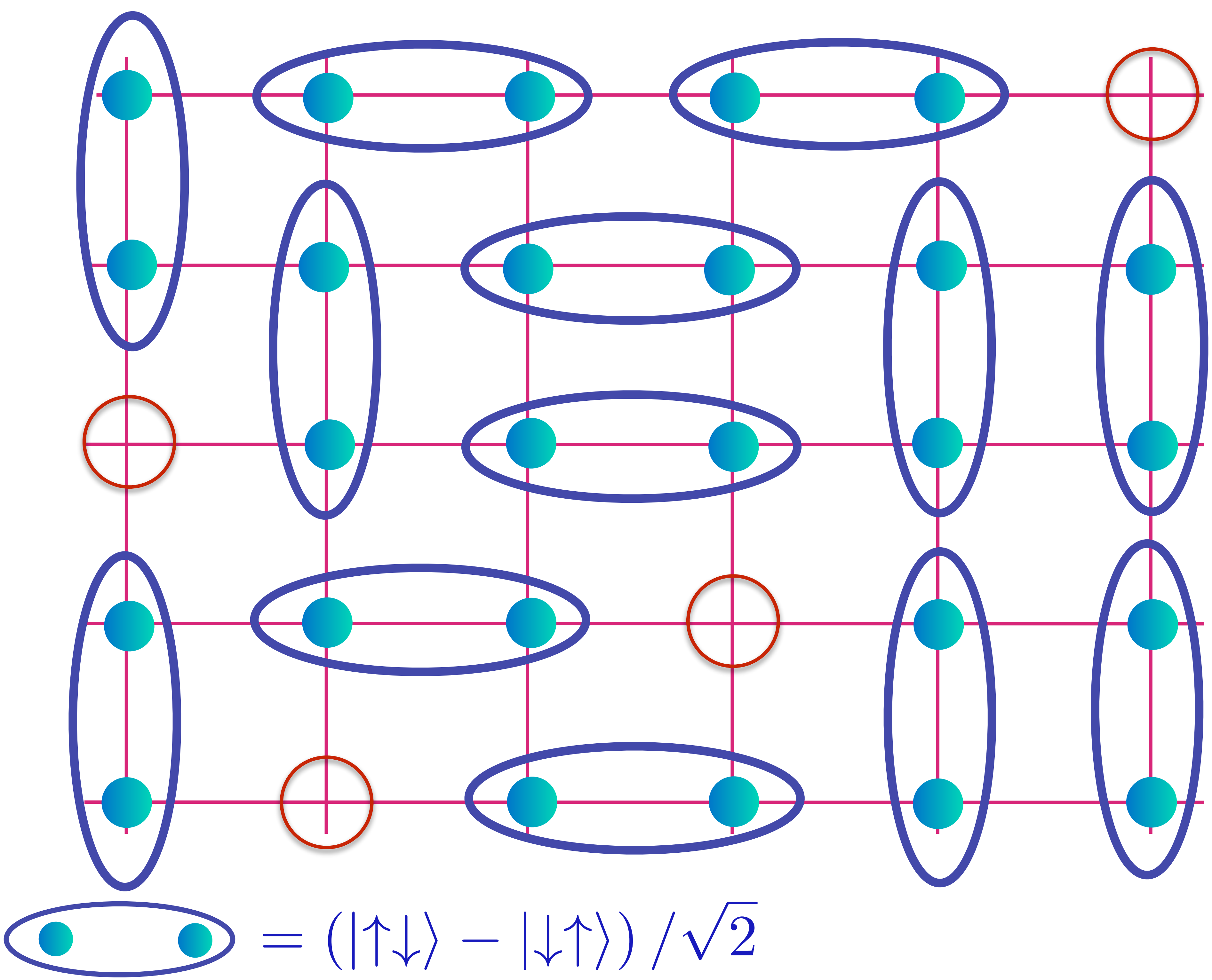


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

Spin liquid with density *p* of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)

N. Read and B. Chakraborty, PRB **40**, 7133 (1989)

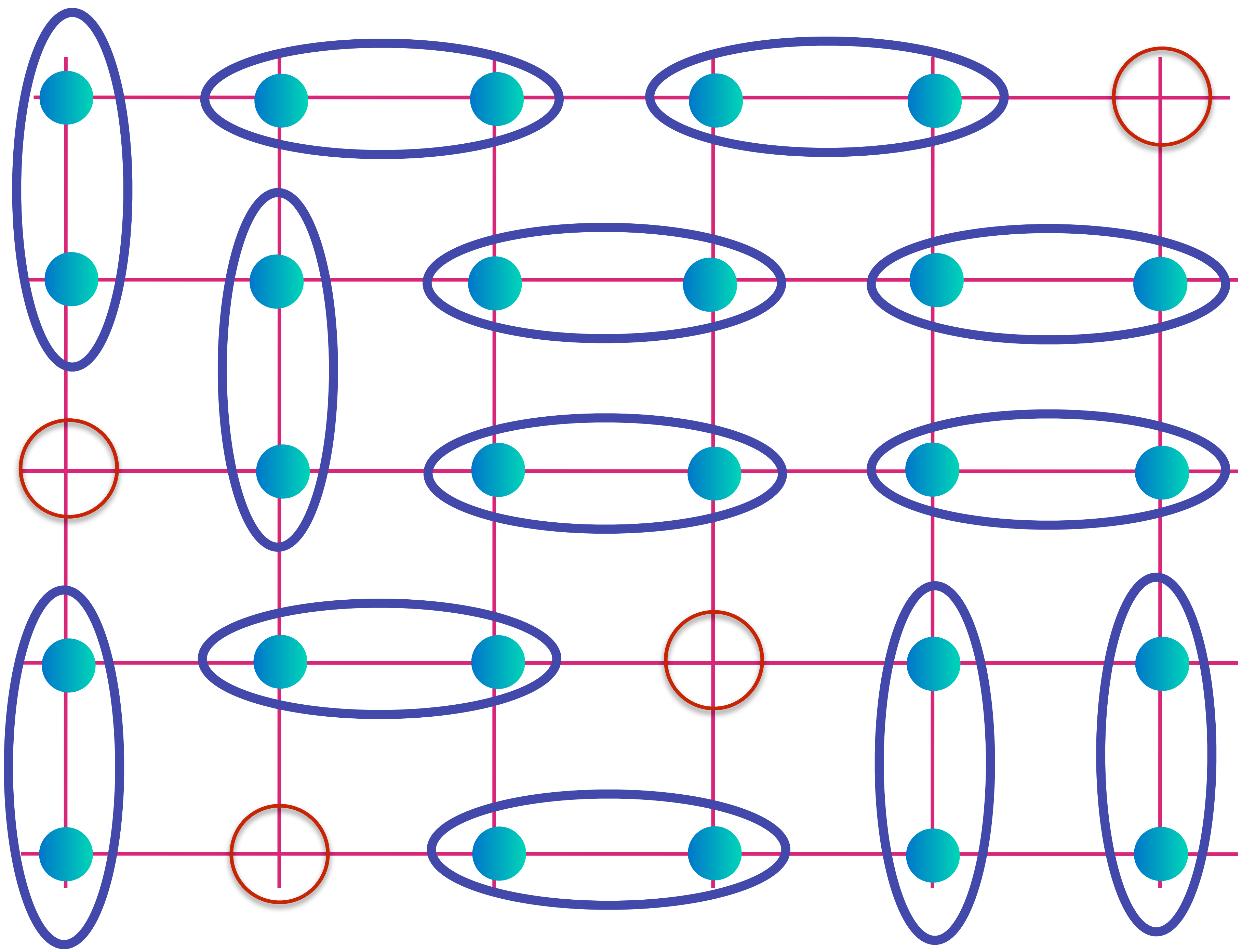


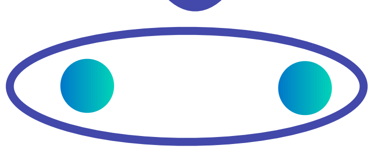
$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

Spin liquid with density p of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)

N. Read and B. Chakraborty, PRB **40**, 7133 (1989)

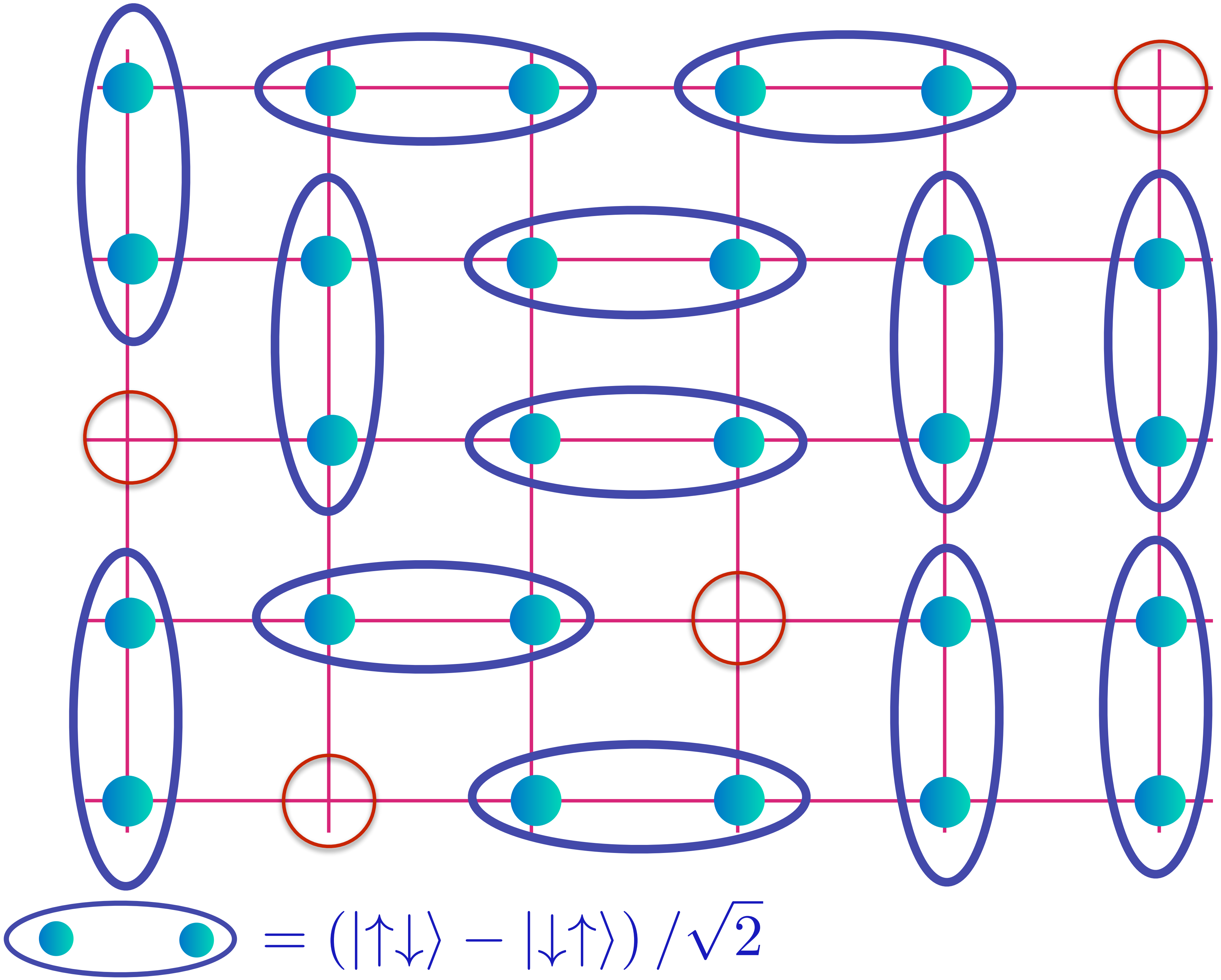


 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

Spin liquid with density *p* of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)

N. Read and B. Chakraborty, PRB **40**, 7133 (1989)

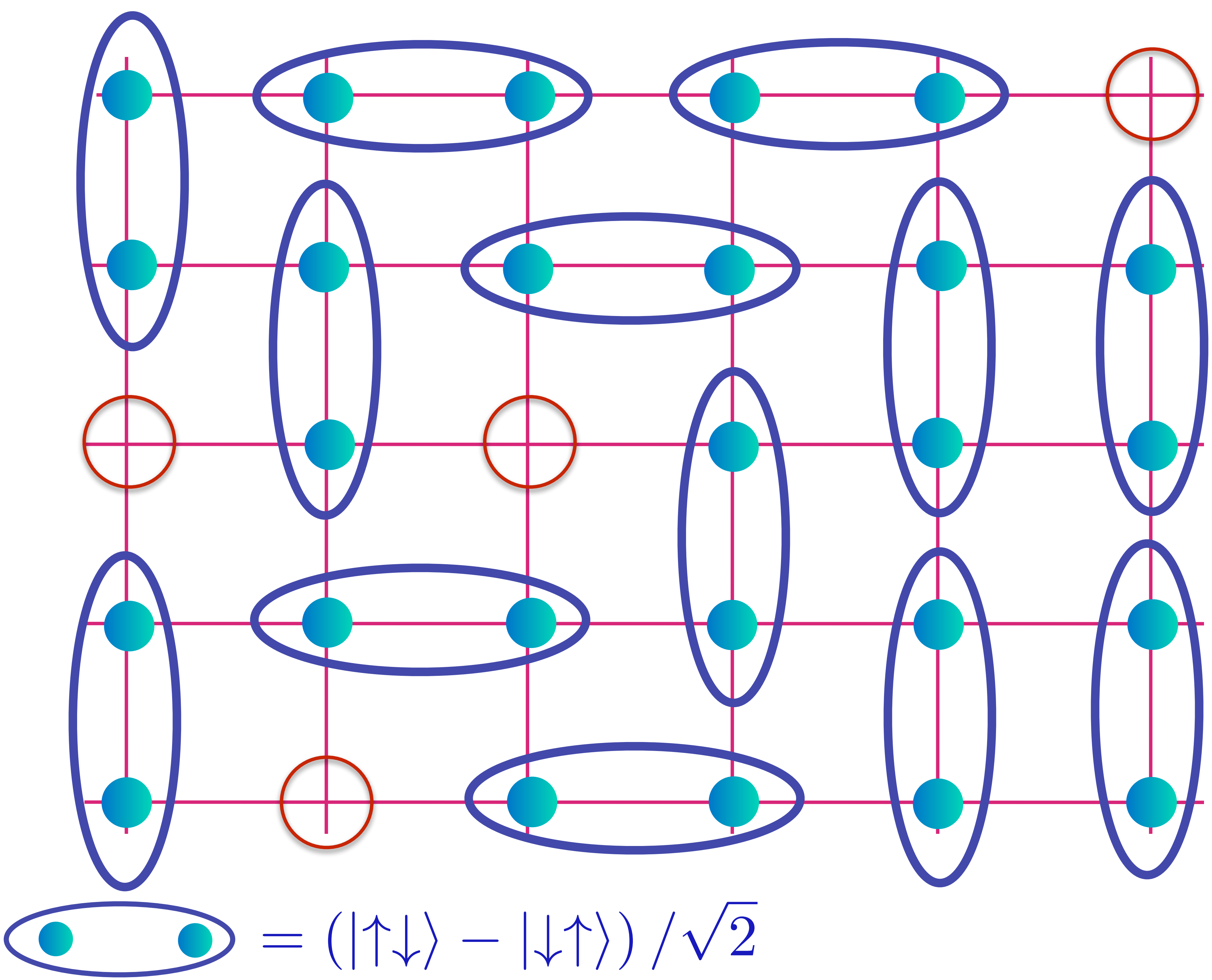


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

Spin liquid with density p of spinless, charge +e “holons”. These can form a Fermi surface of size p, but this is not visible in electron photo-emission

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)

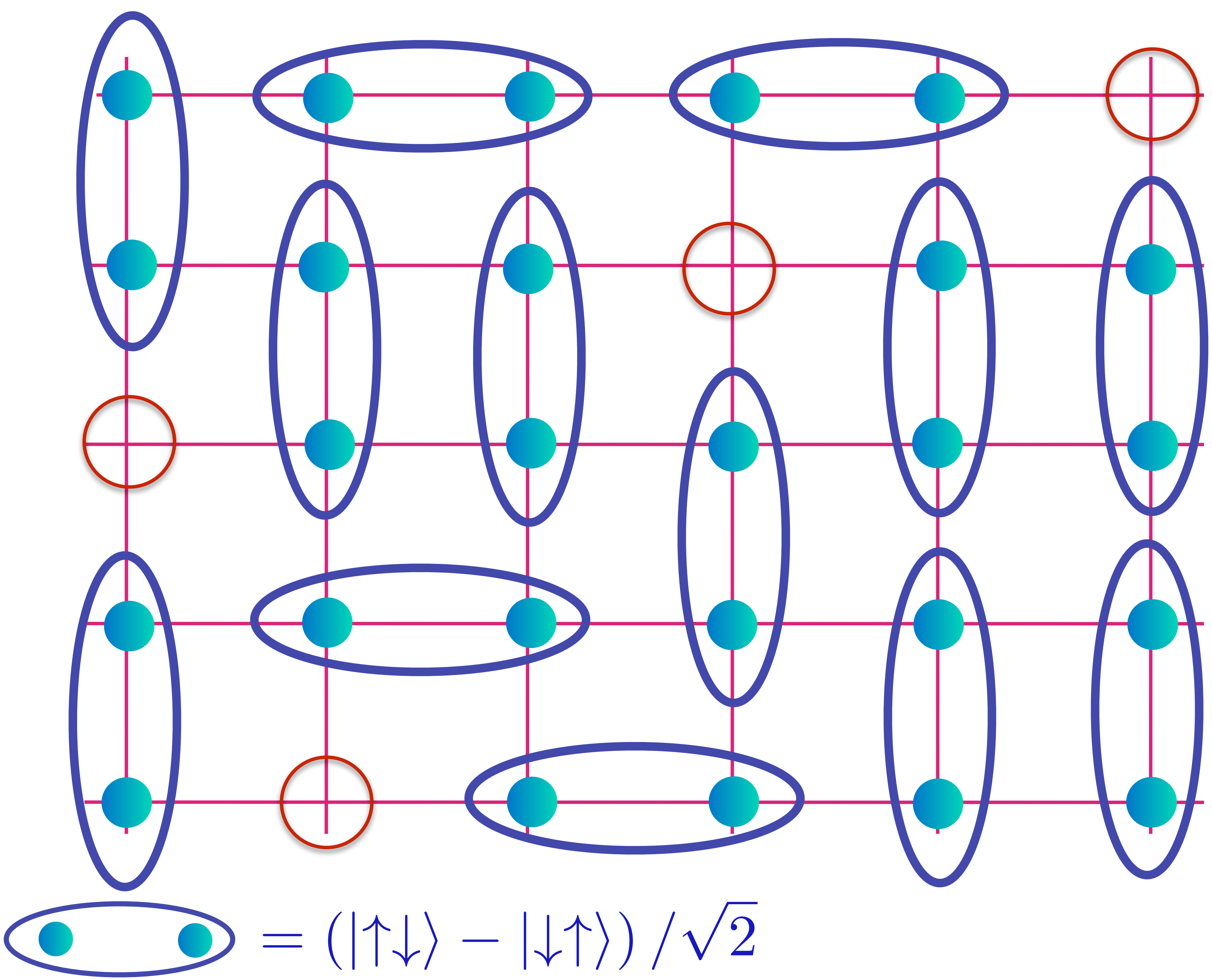
N. Read and B. Chakraborty, PRB **40**, 7133 (1989)



$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

Spin liquid with density *p* of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)
N. Read and B. Chakraborty, PRB **40**, 7133 (1989)

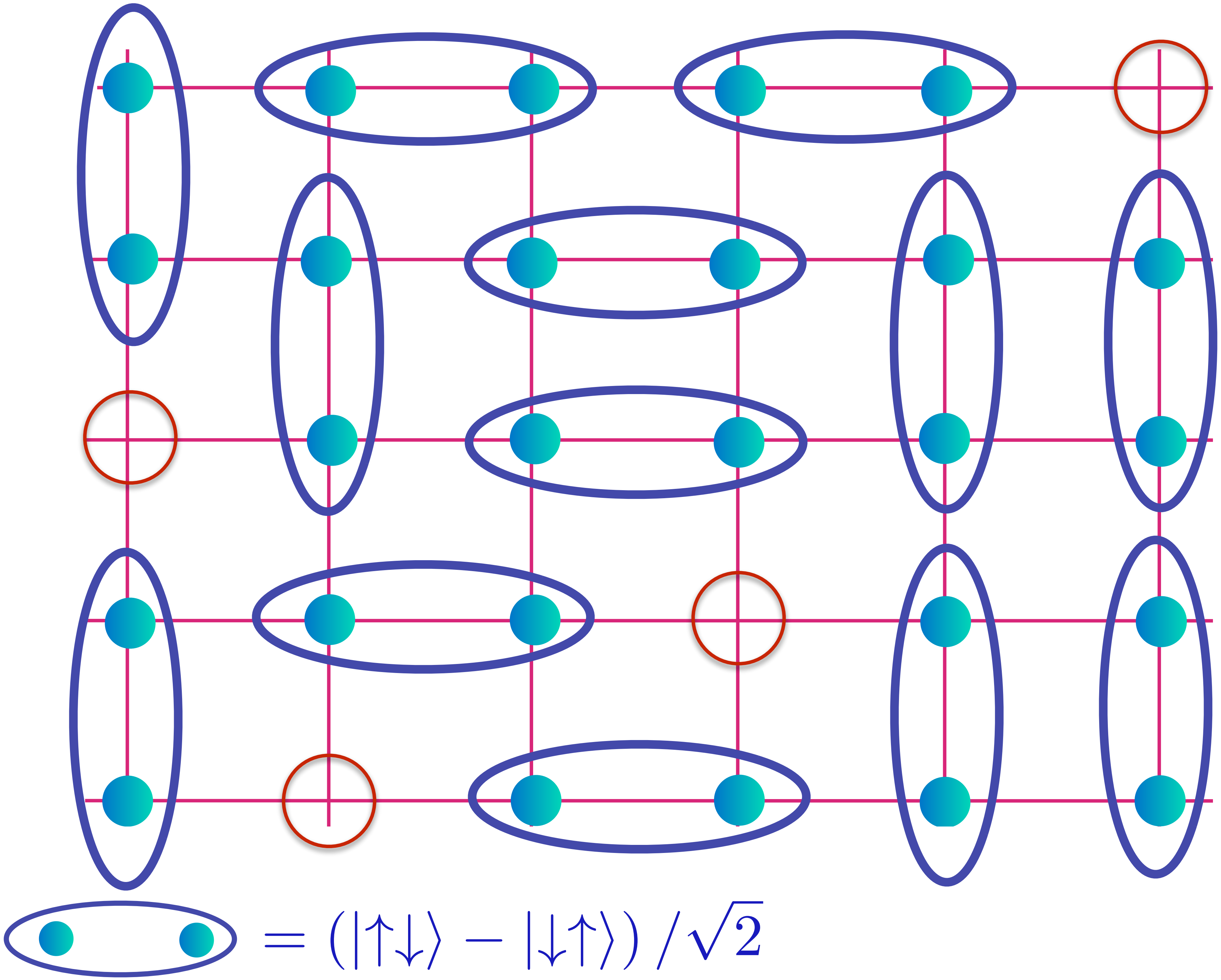


$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

Spin liquid with density *p* of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

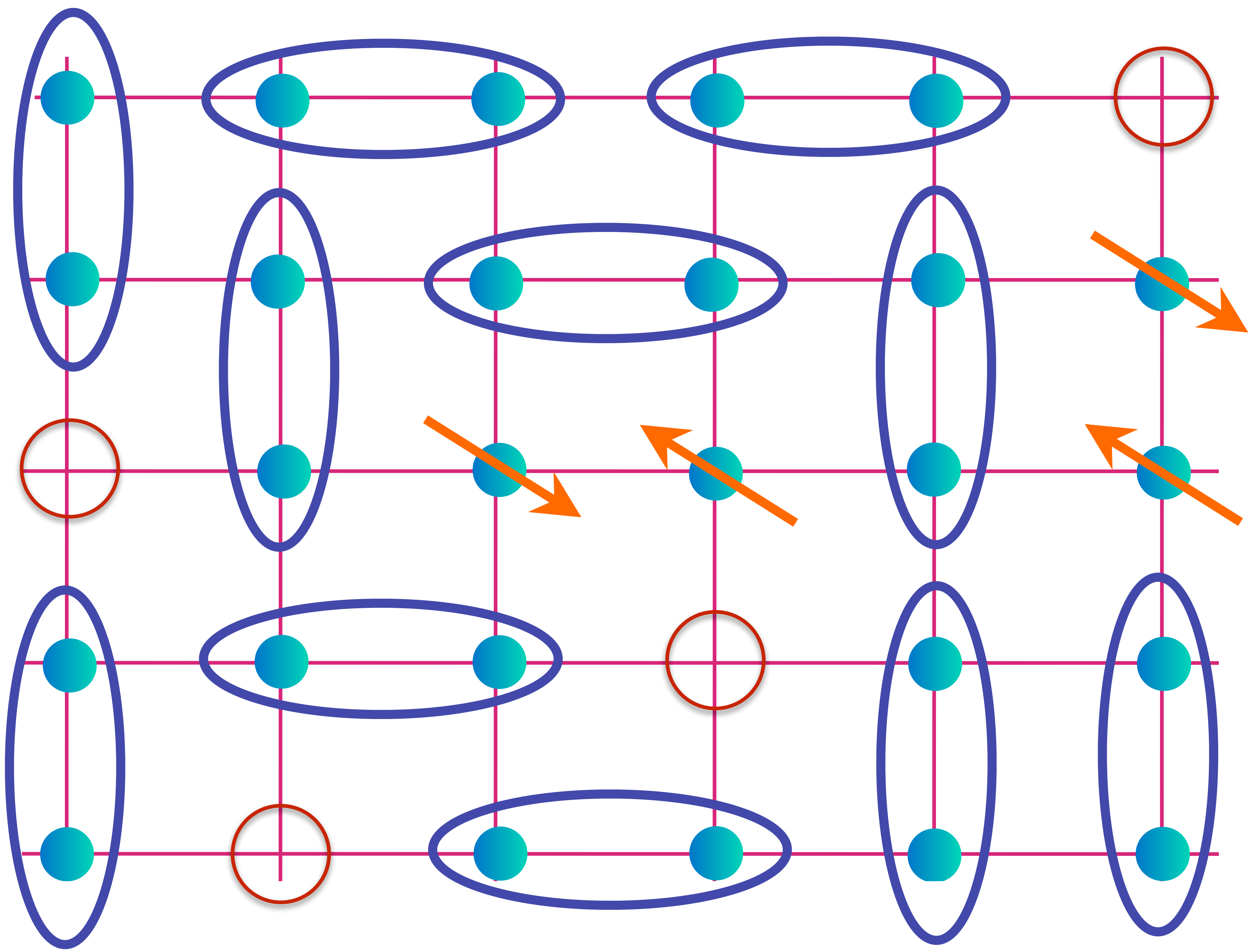
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)

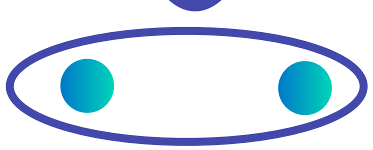
N. Read and B. Chakraborty, PRB **40**, 7133 (1989)

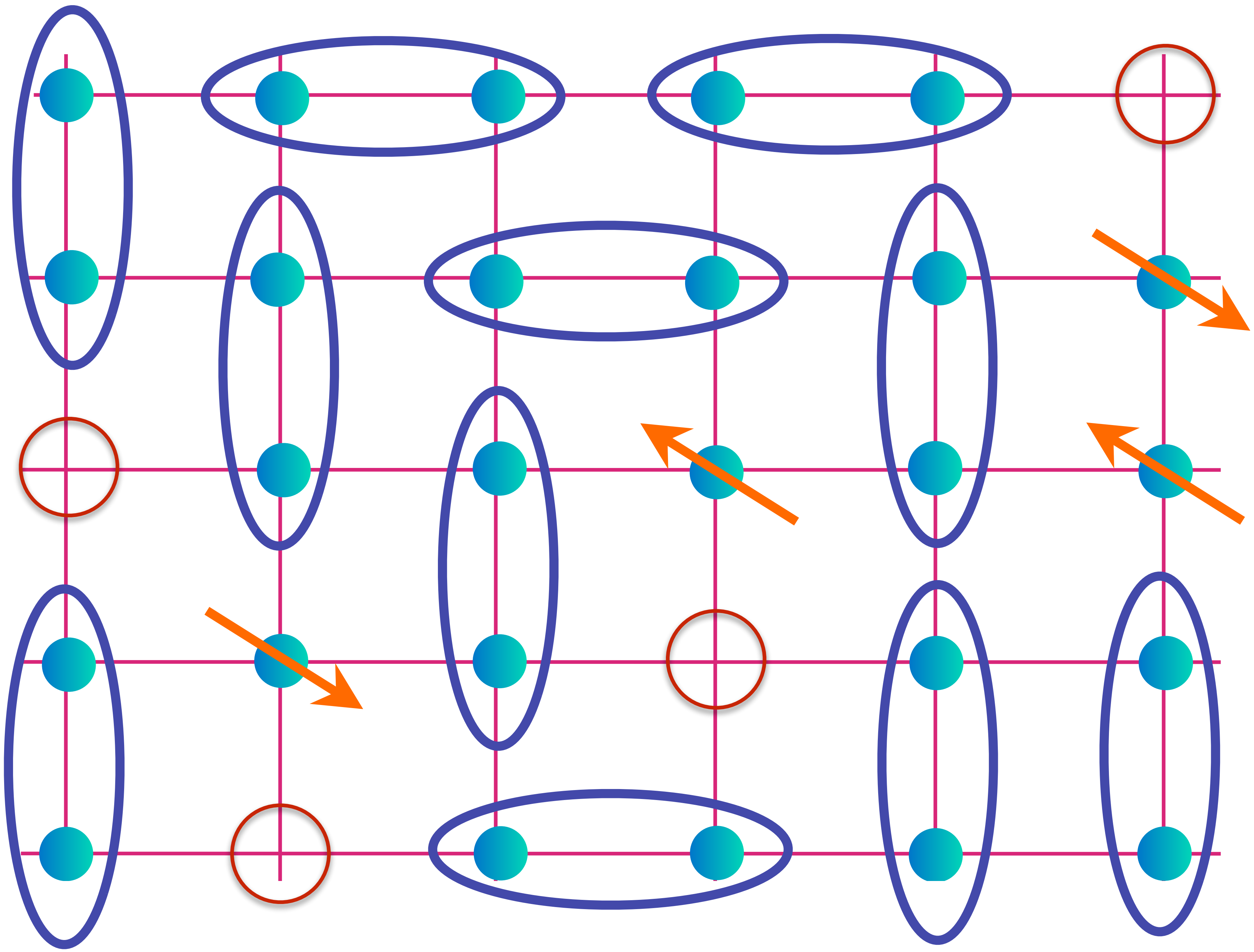


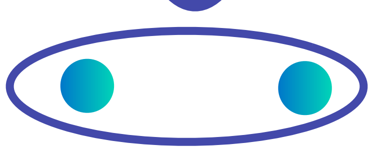
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

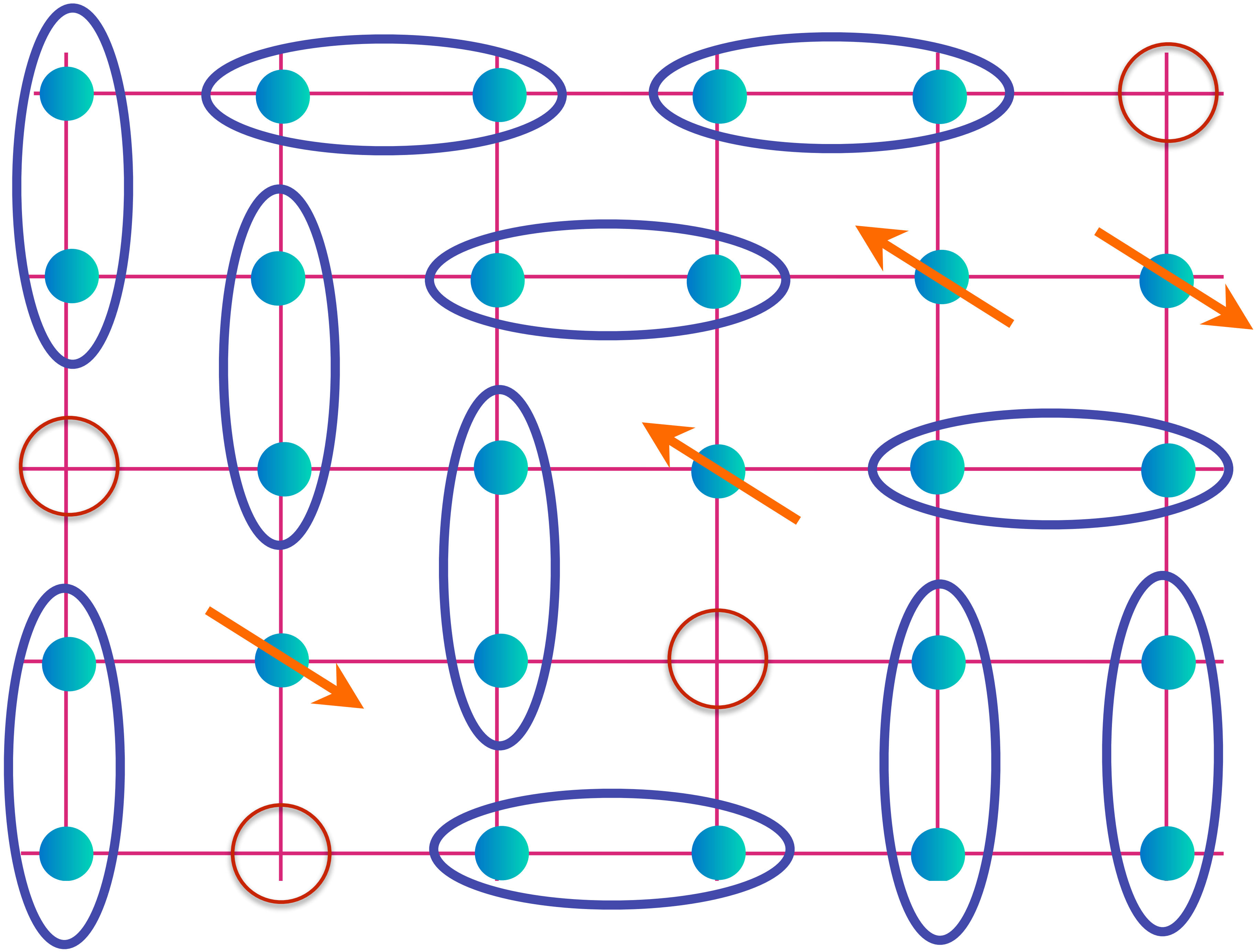
Spin liquid with density p of spinless, charge +e "holons". These can form a Fermi surface of size p, but this is not visible in electron photo-emission

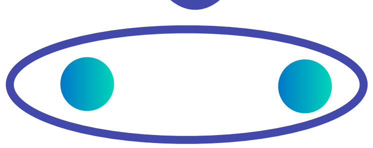


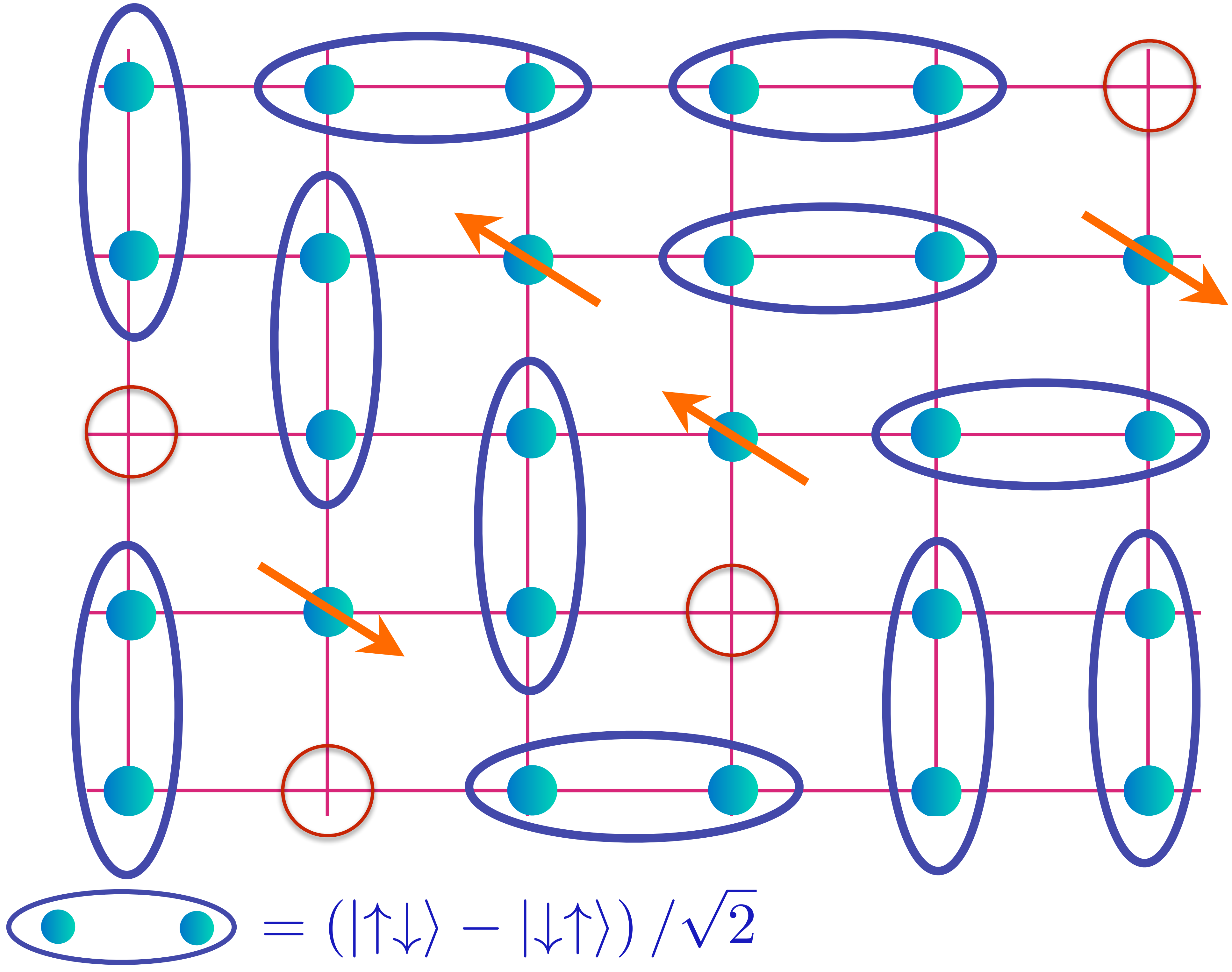
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



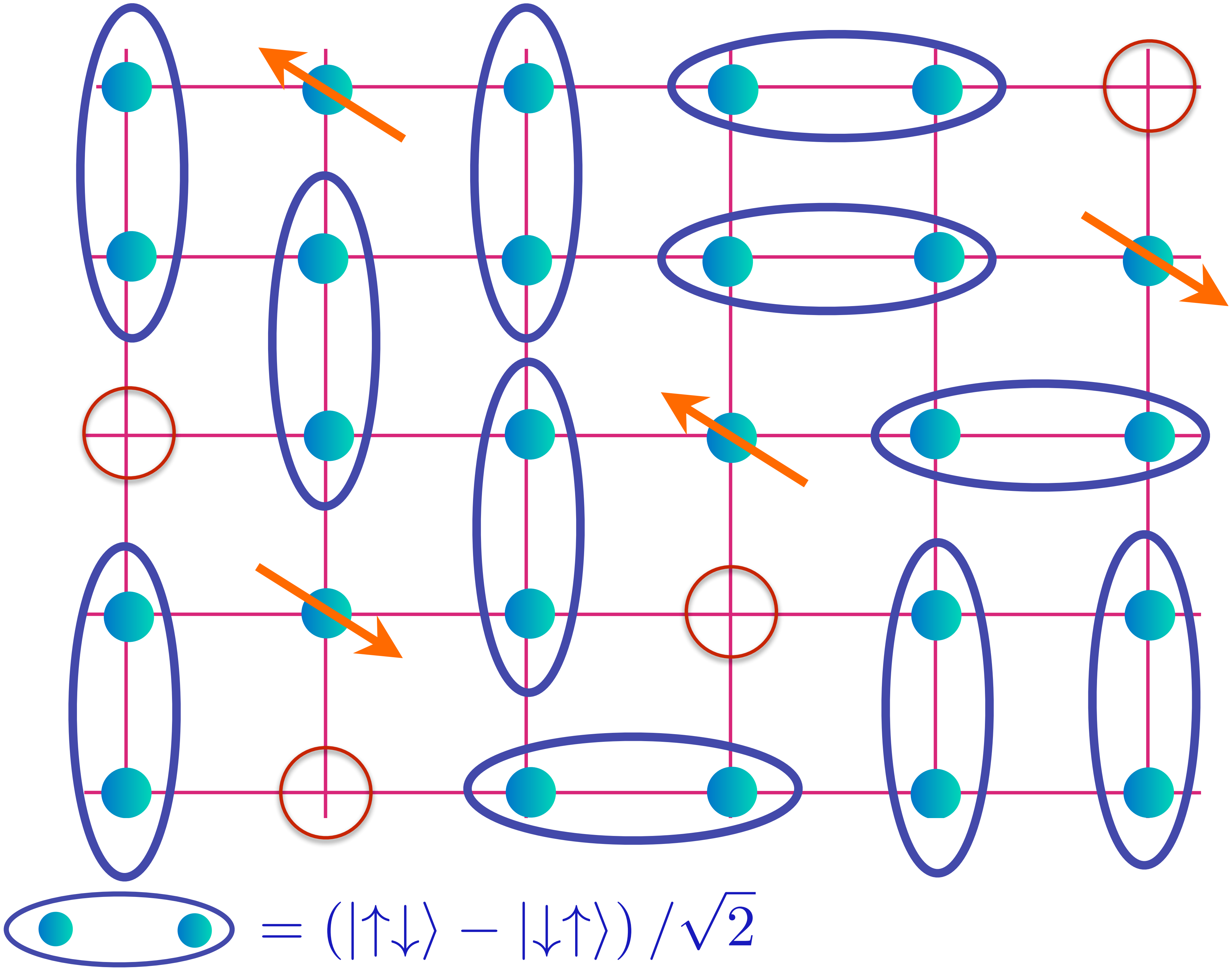
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

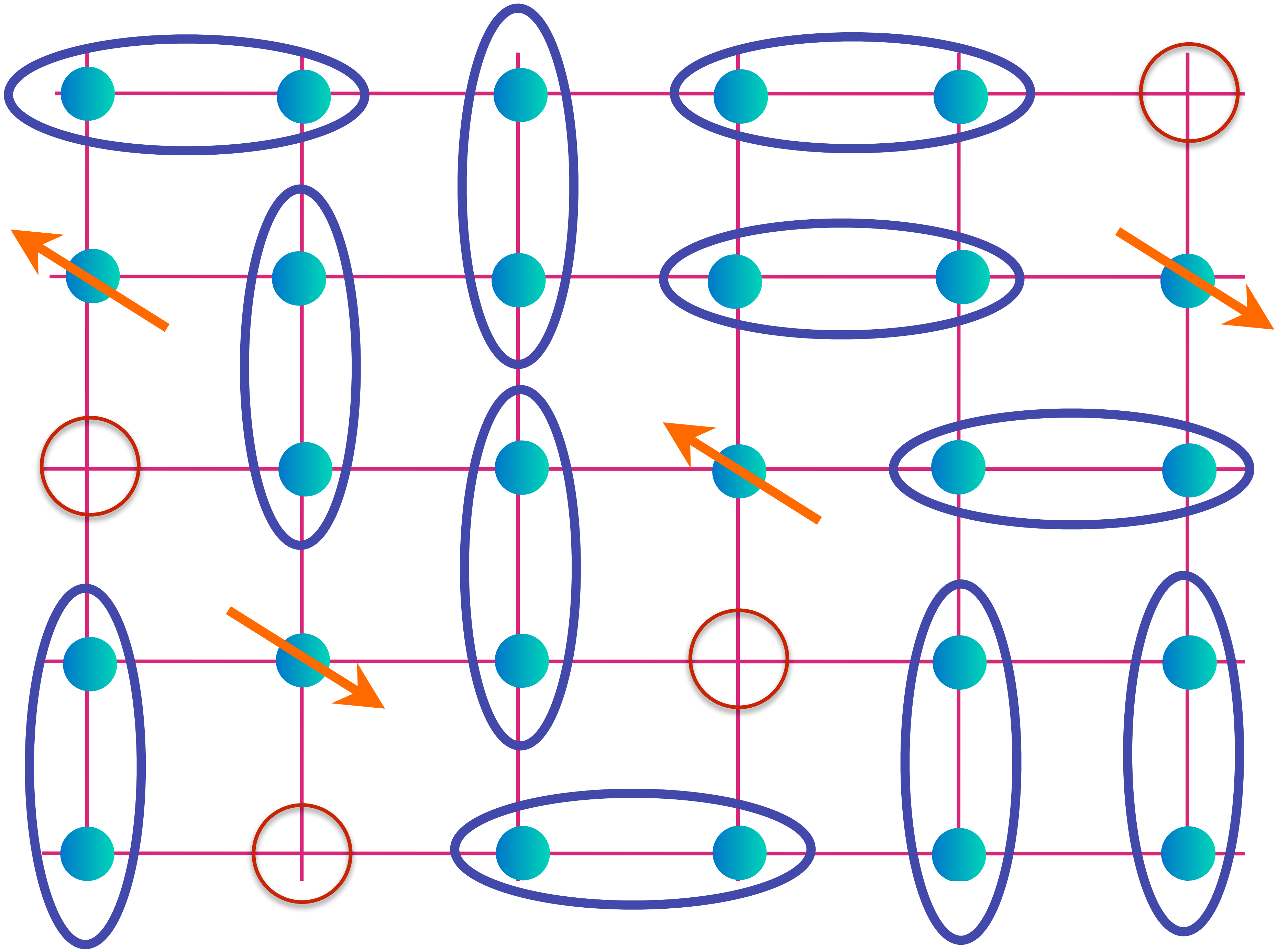


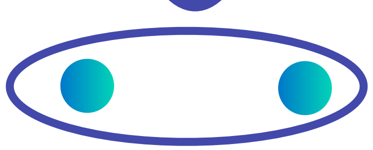
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

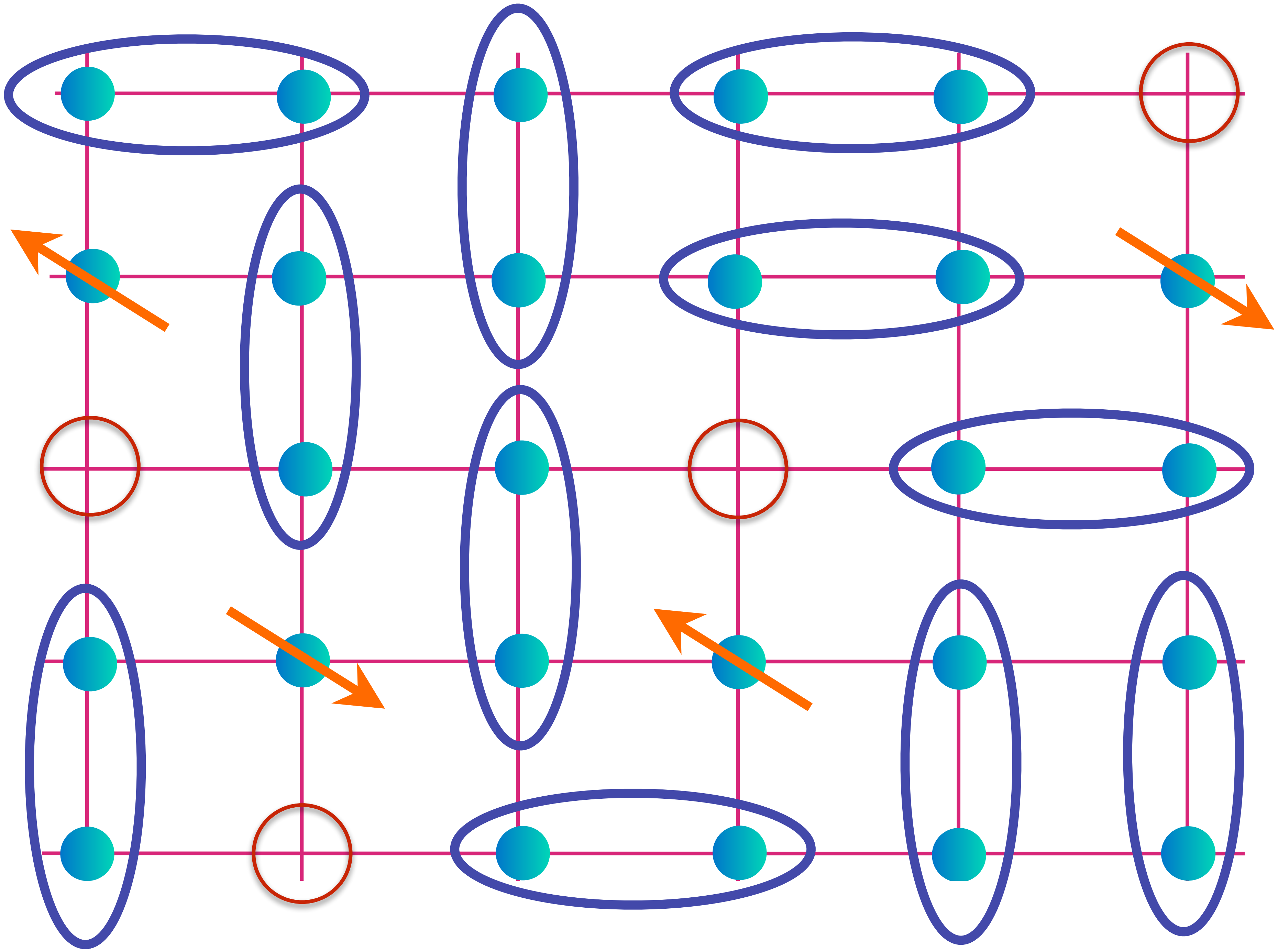


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

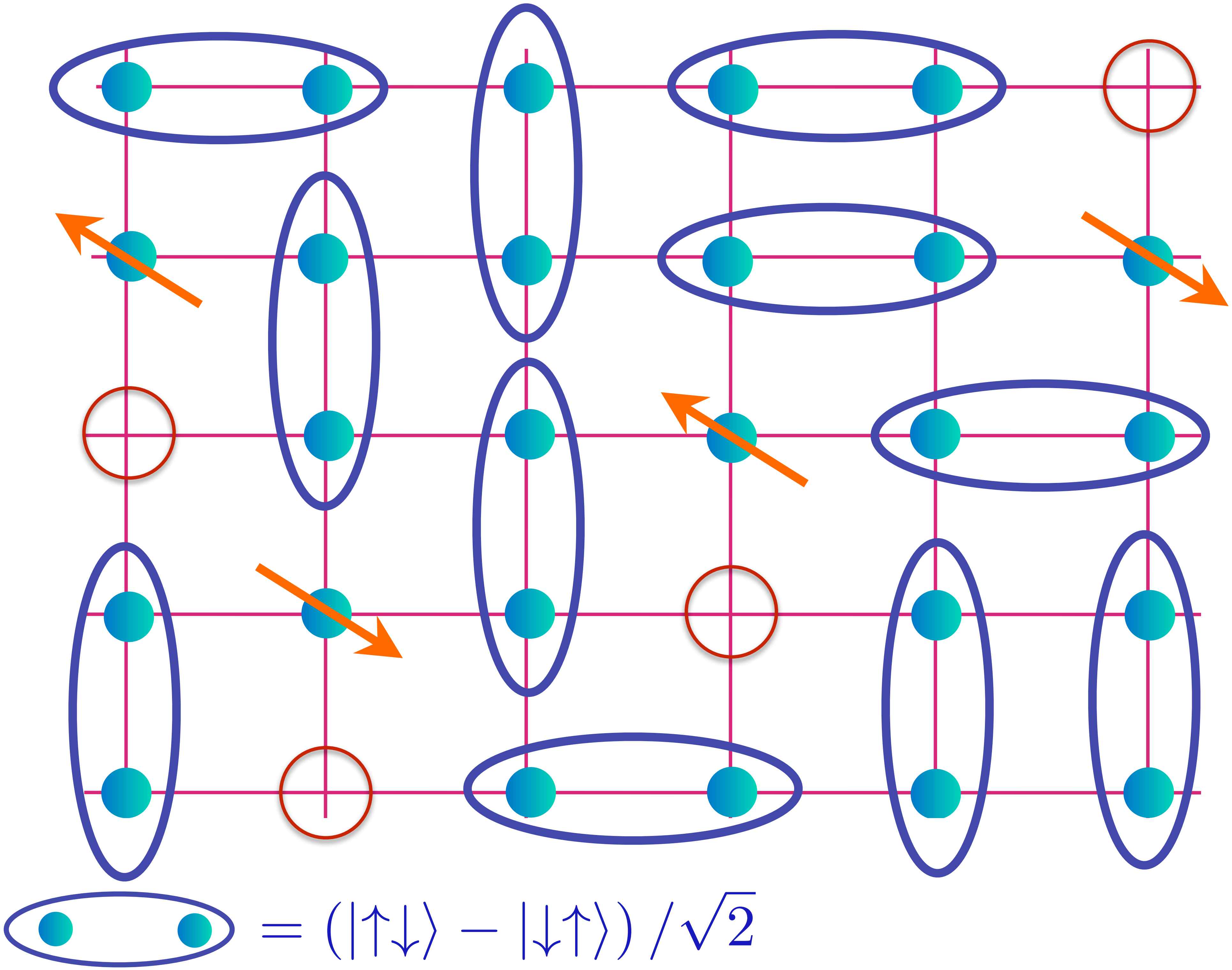

= (|↑↓⟩ − |↓↑⟩) / √2



 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



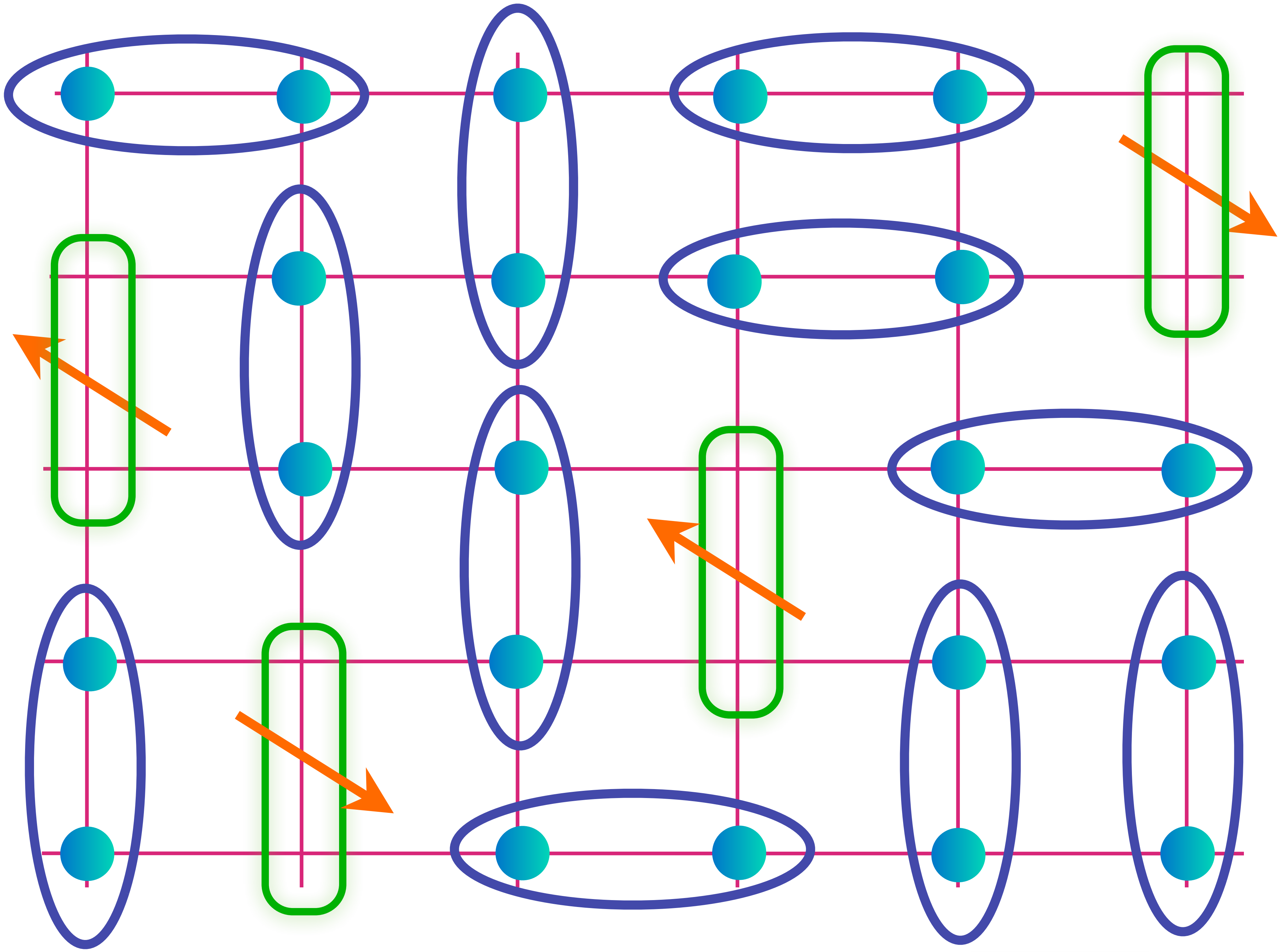
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$



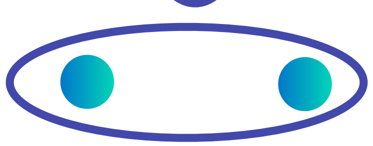
$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

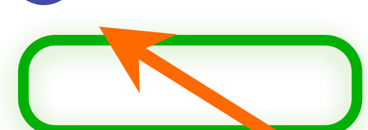
FL*

S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

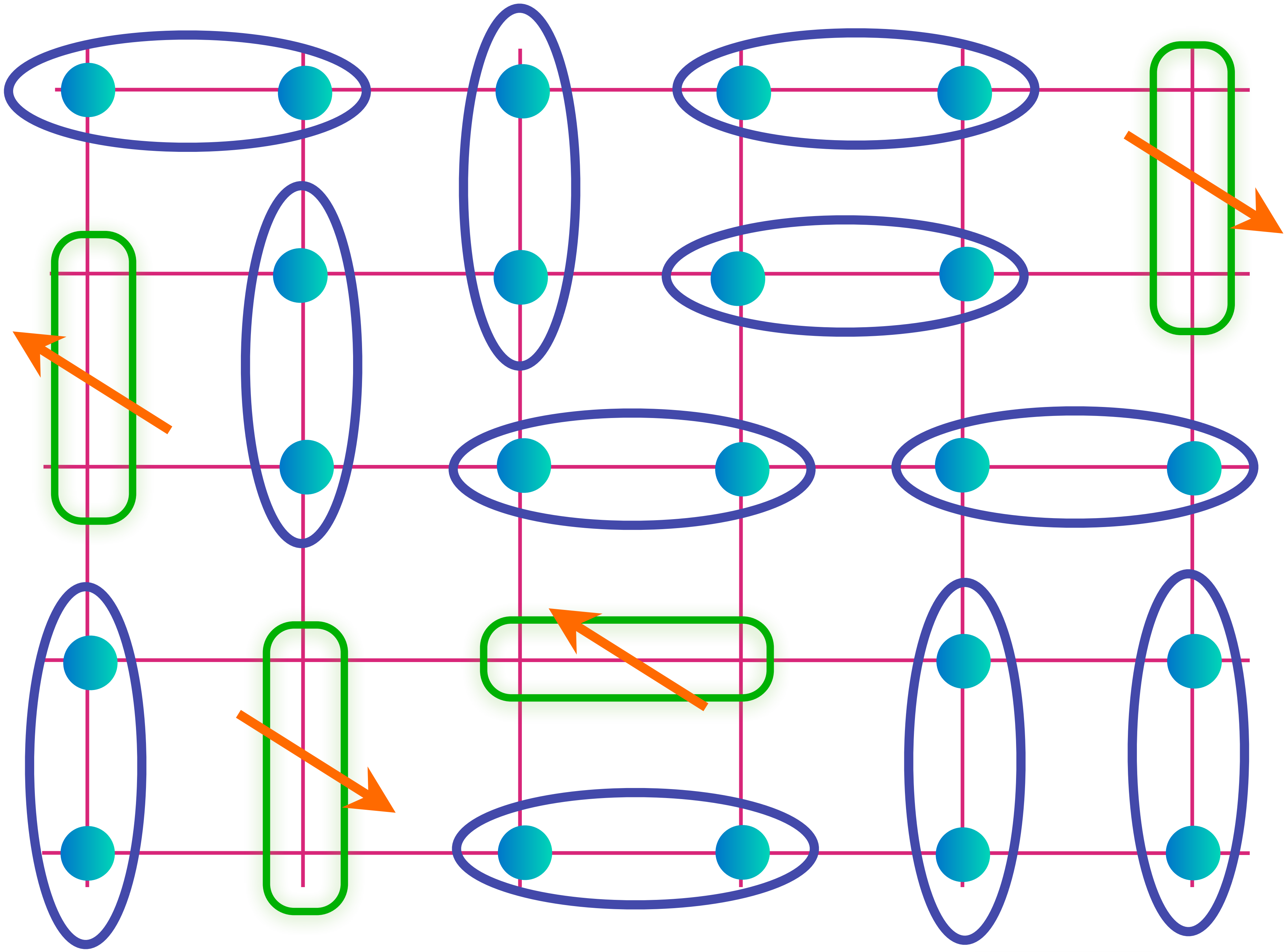
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$

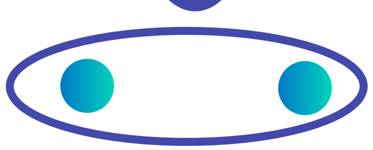
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

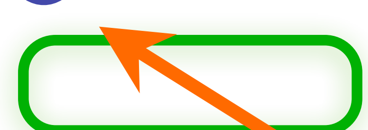
FL*

S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

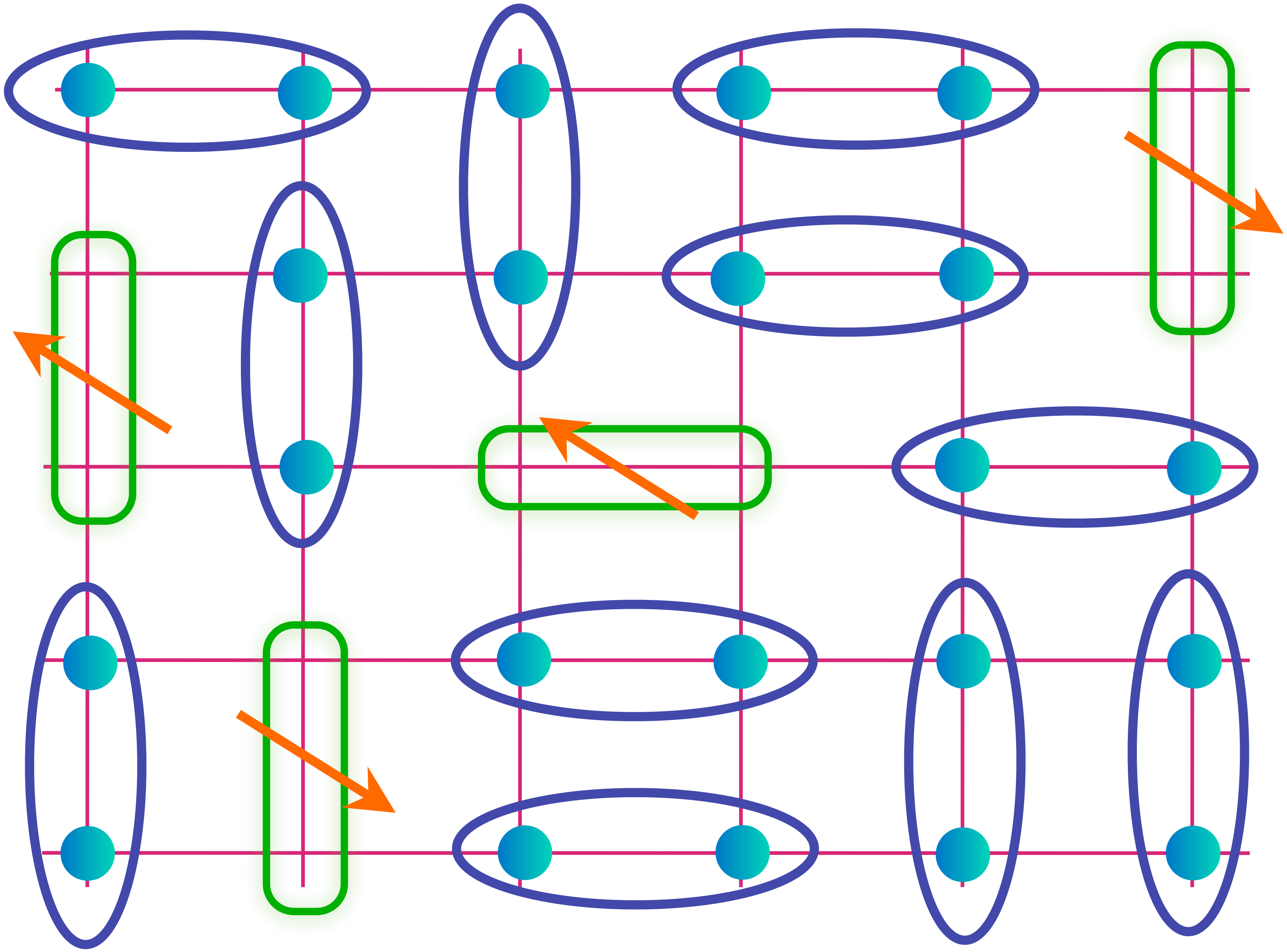
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle\right)/\sqrt{2}$

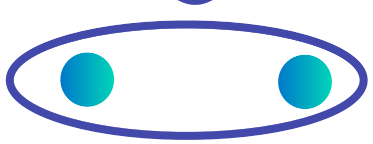
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

FL*

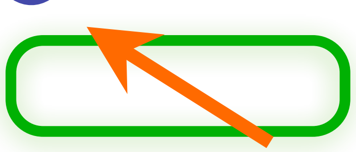
S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission



$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

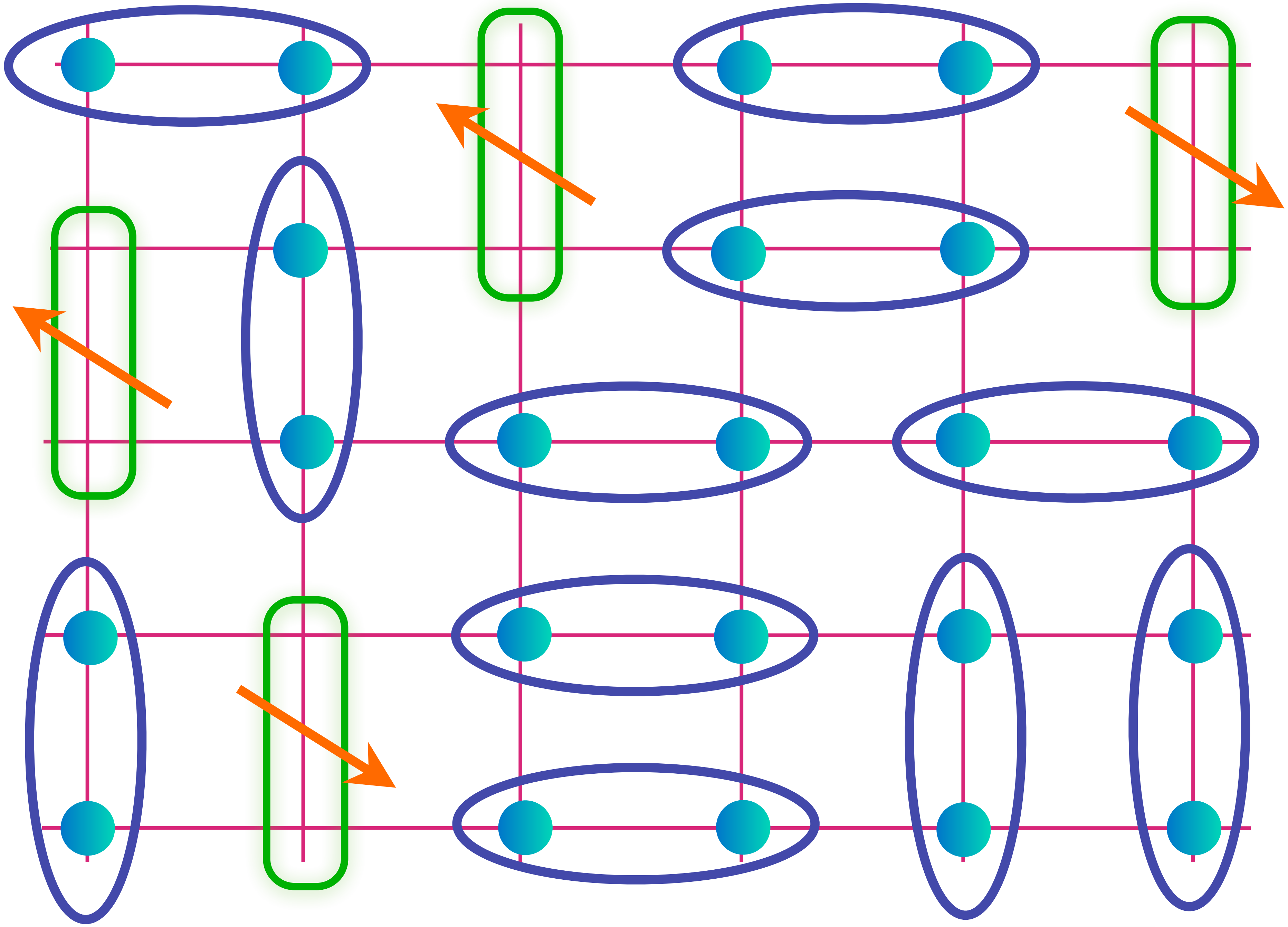


$= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$

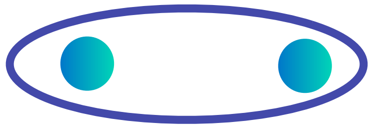
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

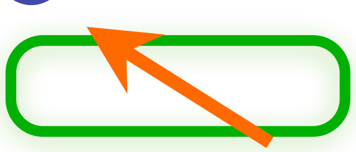
FL*

S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

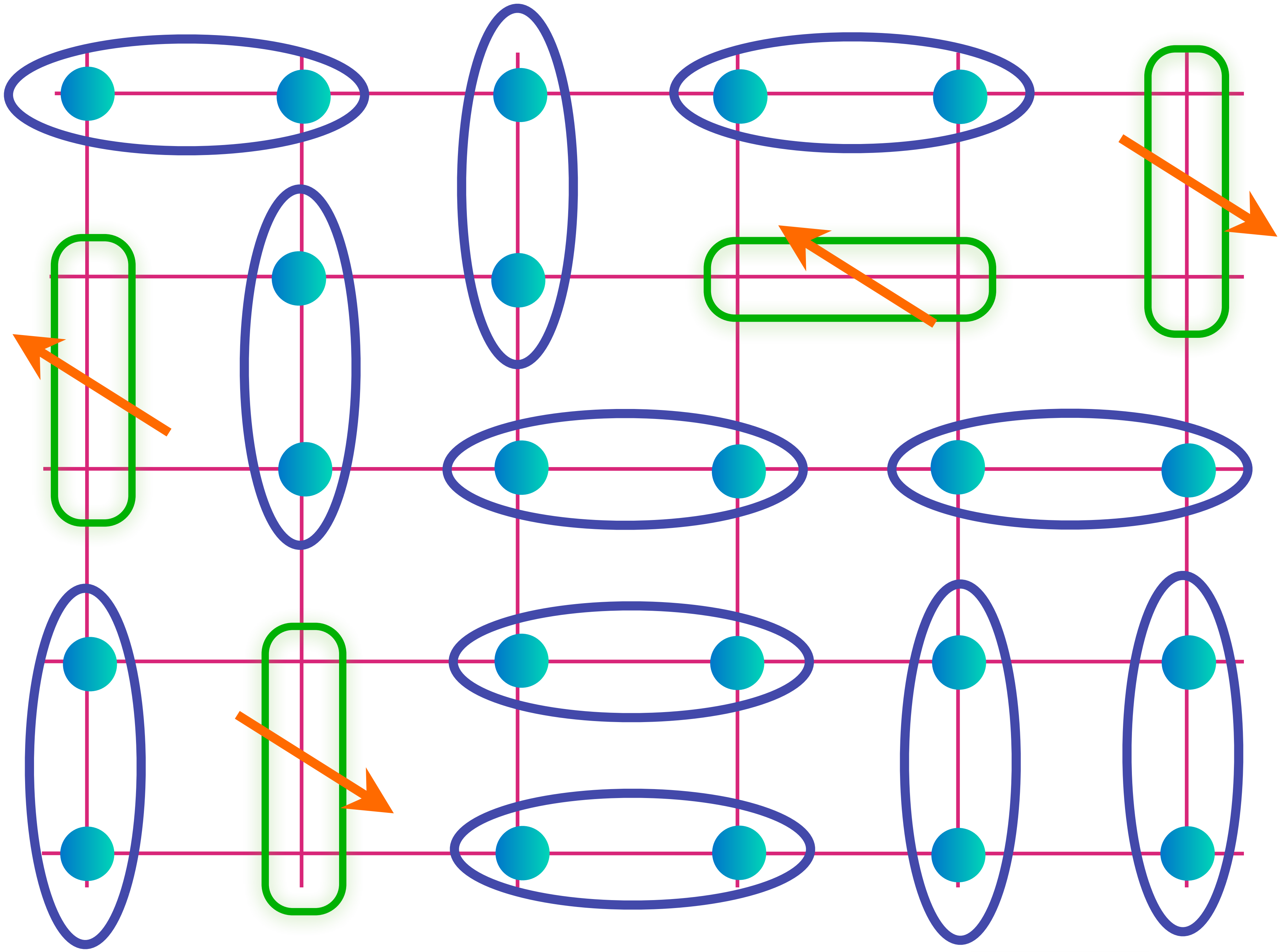
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$

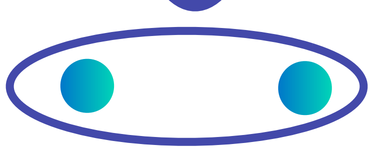
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

FL*

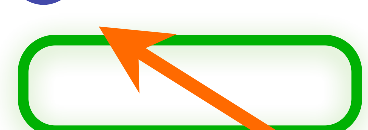
S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission



$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

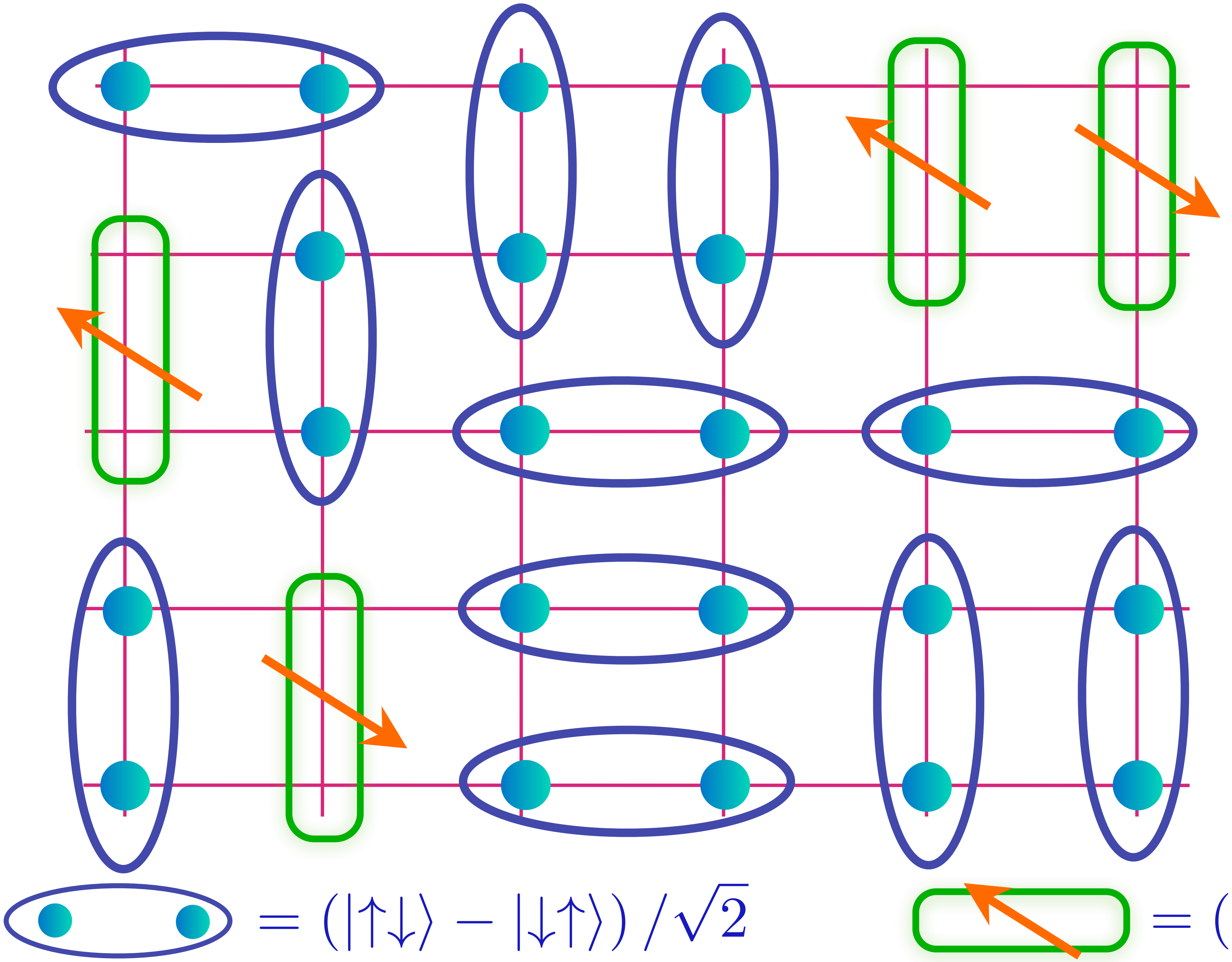


$= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

FL*

S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$

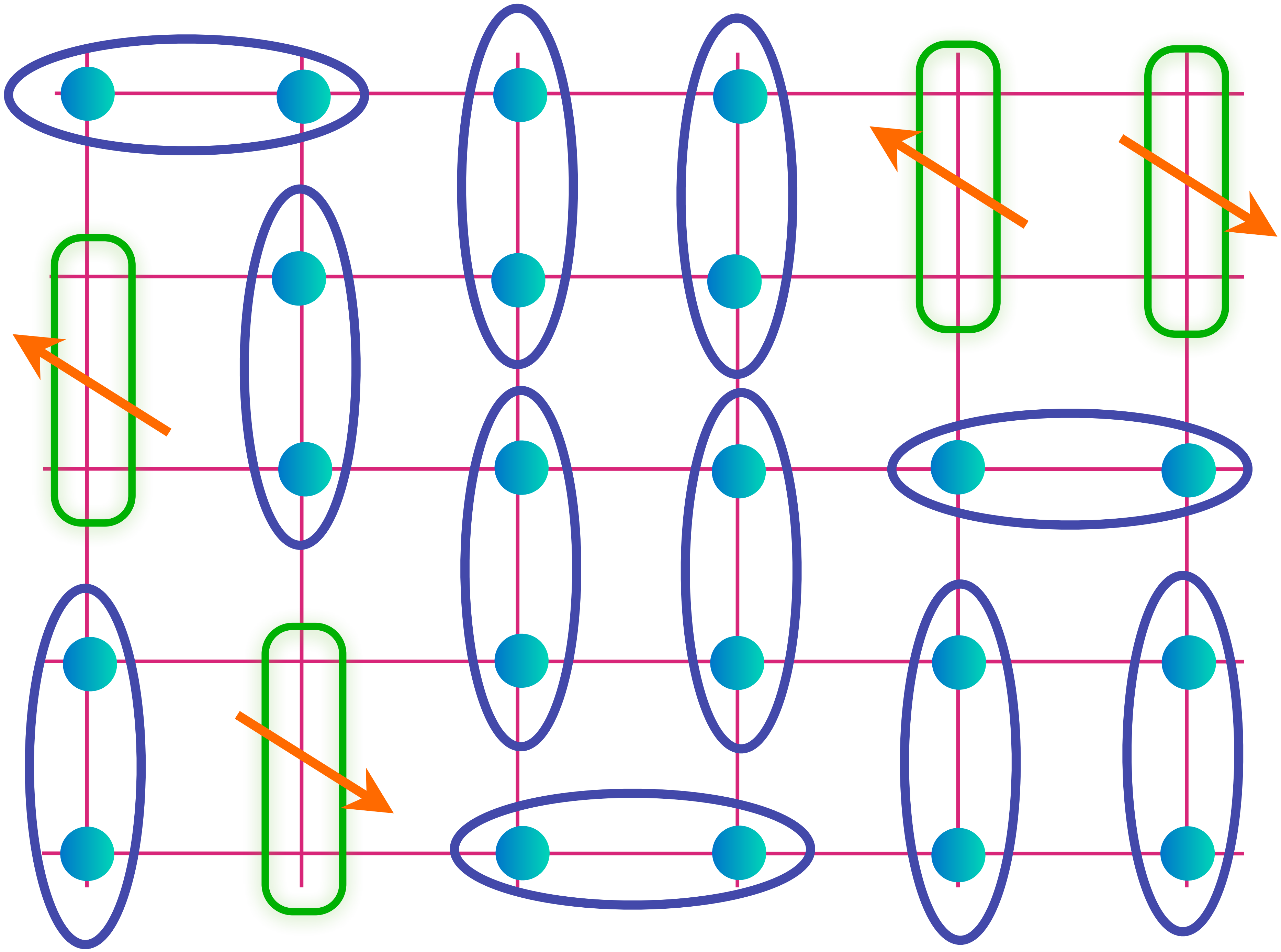
$$= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$$

Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

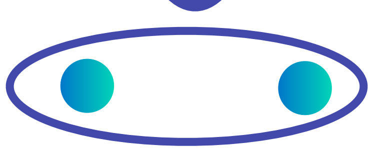
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

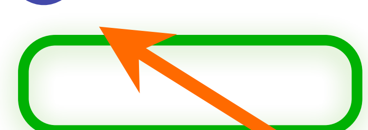
FL*

S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

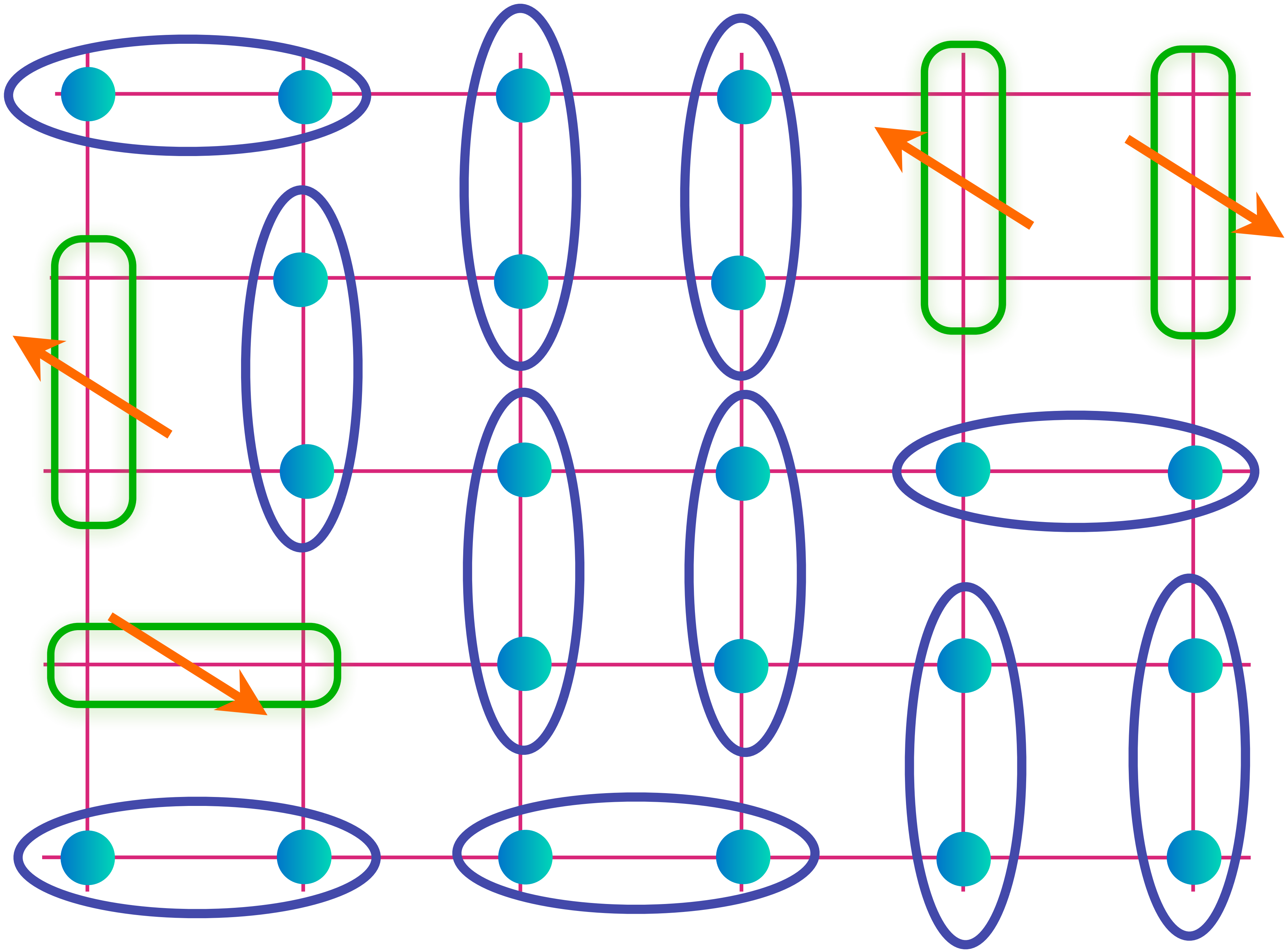
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

 $= (|\uparrow\circ\rangle + |\circ\uparrow\rangle)/\sqrt{2}$

M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

FL*

S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, PRB **75**, 235122 (2007)



Mobile S=1/2, charge +e fermionic dimers: form a Fermi surface of size p visible in electron photo-emission

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$

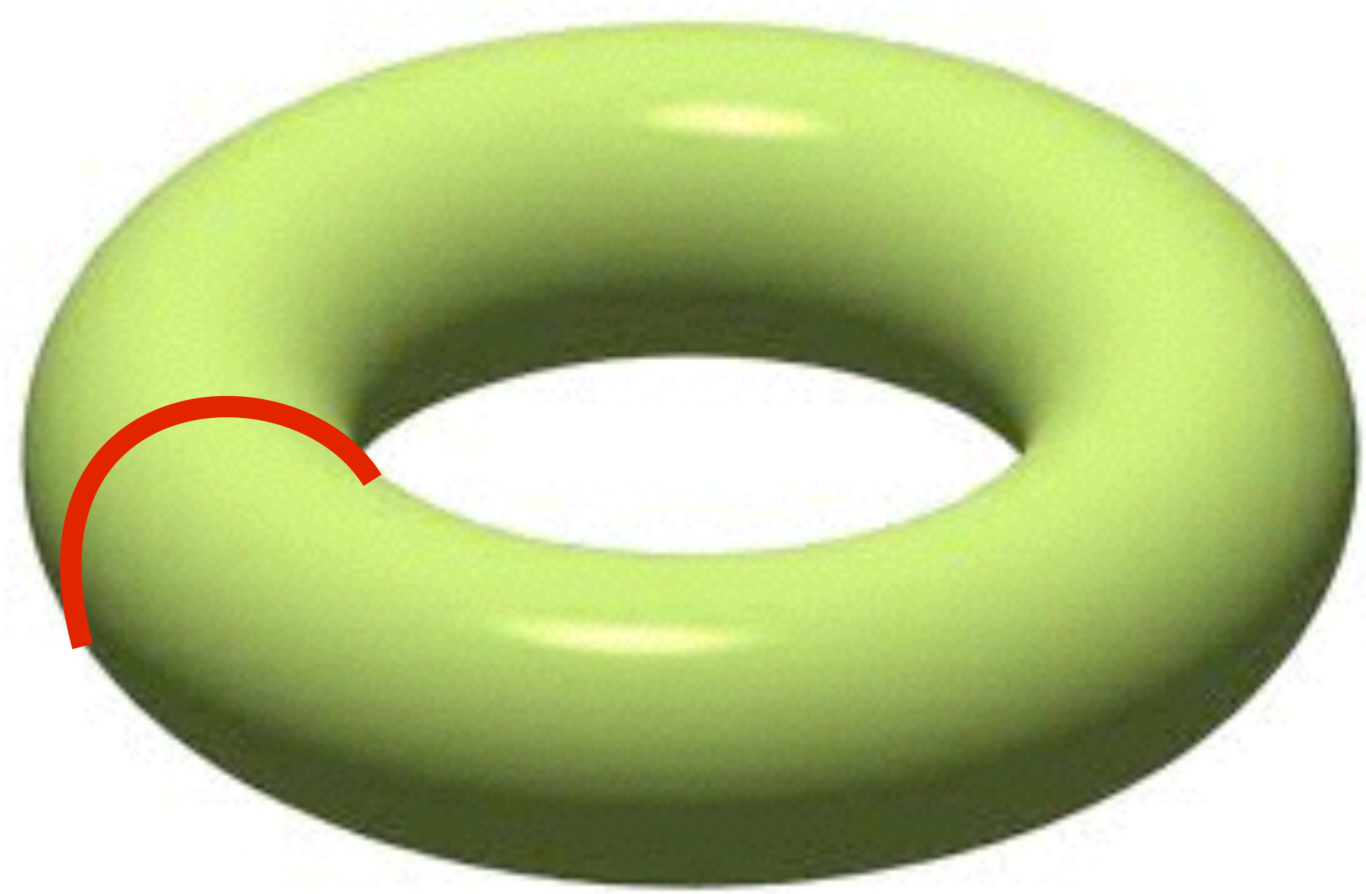
$$= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$$

M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

Ground state degeneracy

Place FL*
on a torus:

Ground state degeneracy

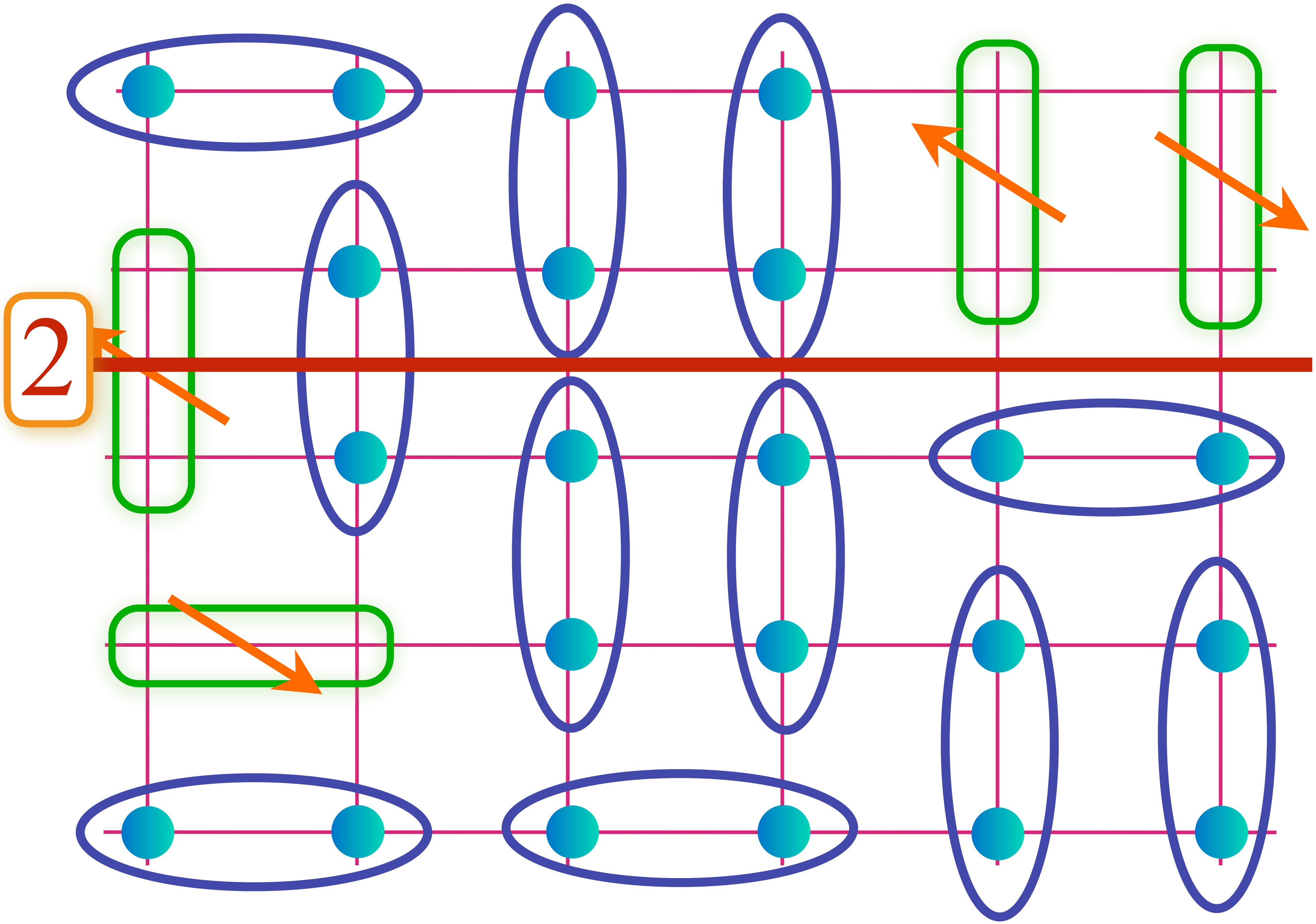


Place FL* on a torus:

obtain "topological" states nearly degenerate with quasiparticle states: number of dimers crossing red line is conserved modulo 2

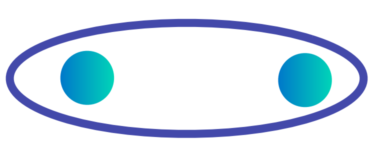
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

FL*

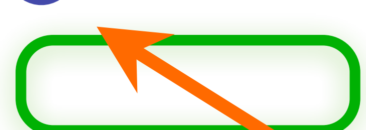


Place FL* on a torus:

obtain "topological" states nearly degenerate with quasiparticle states: number of dimers crossing red line is conserved modulo 2



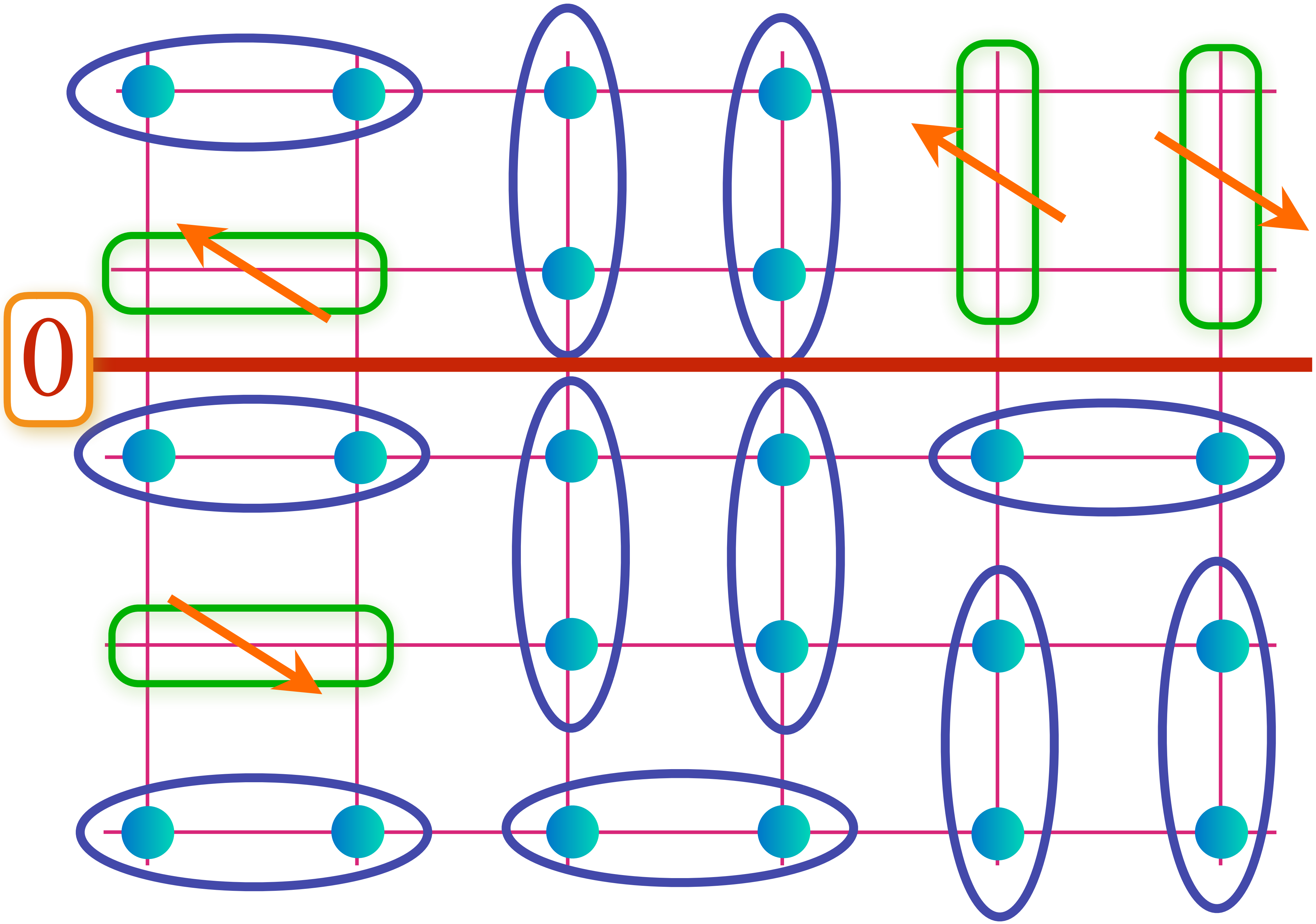
$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$



$= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$

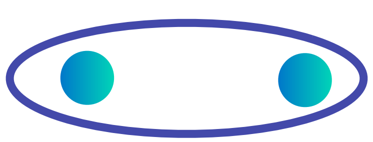
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

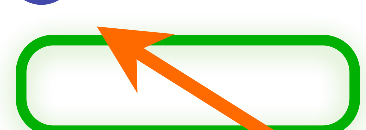
FL*



Place FL* on a torus:

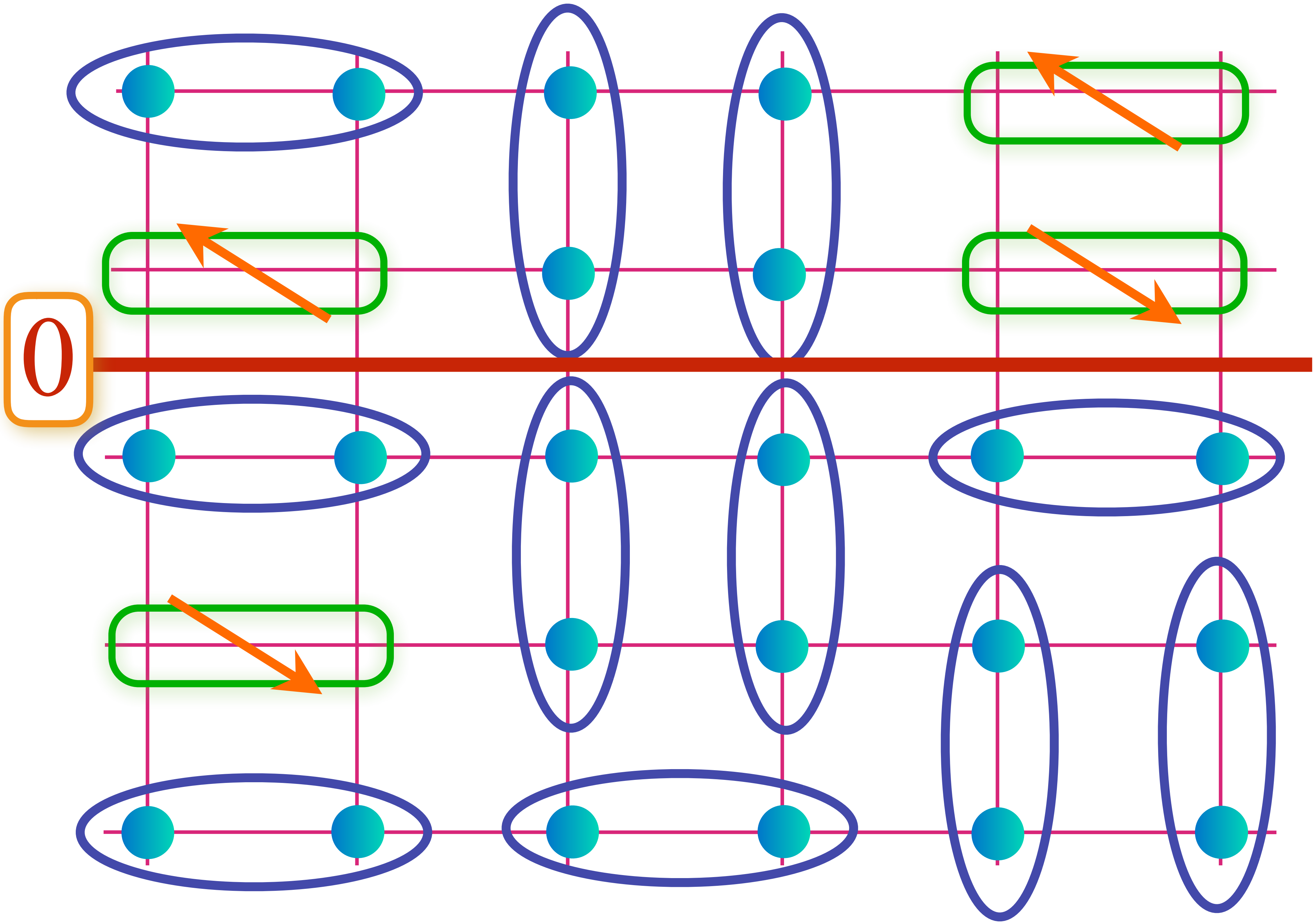
obtain "topological" states nearly degenerate with quasiparticle states: number of dimers crossing red line is conserved modulo 2

 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle\right)/\sqrt{2}$

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

FL*



Place FL* on a torus:

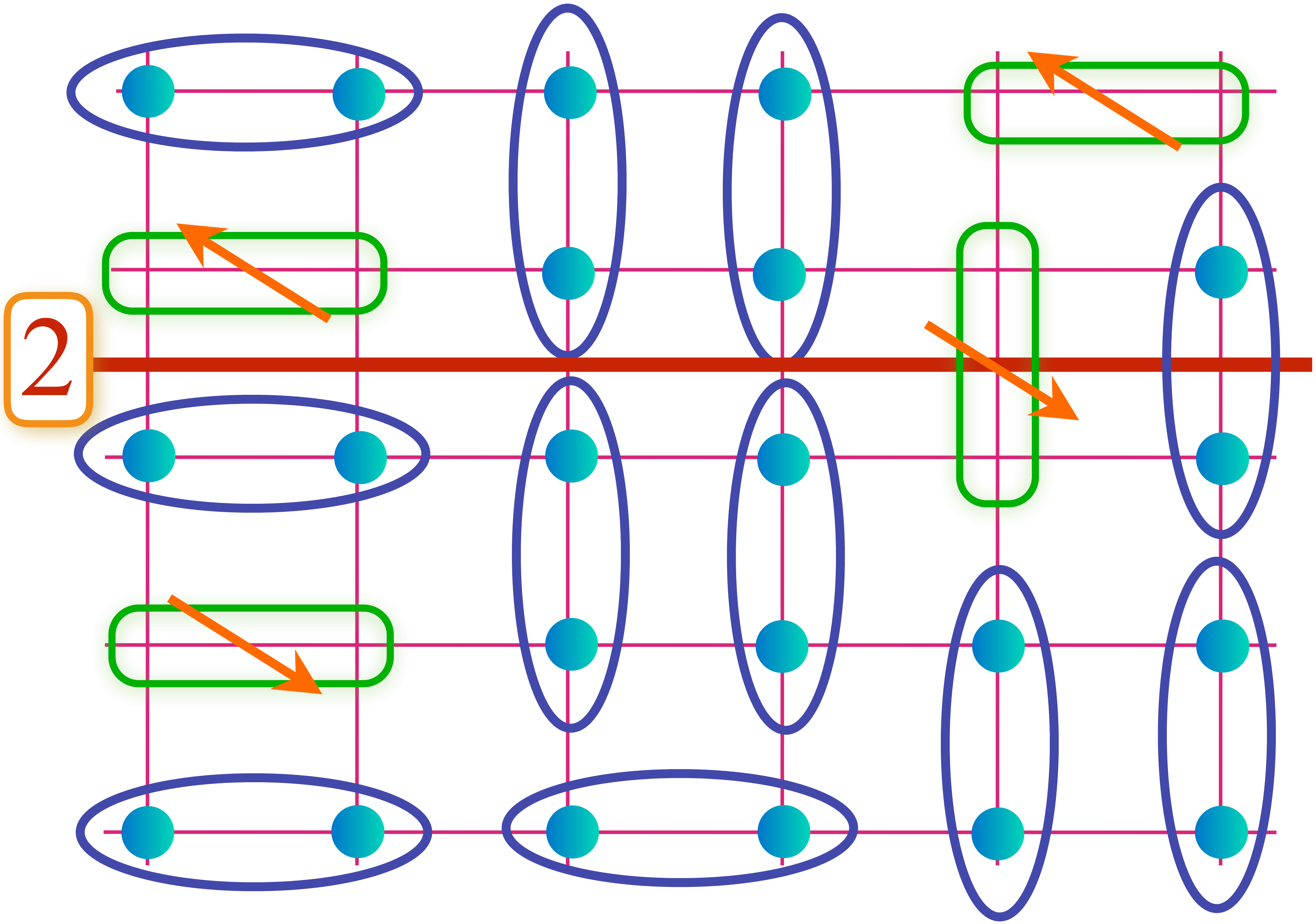
obtain "topological" states nearly degenerate with quasiparticle states: number of dimers crossing red line is conserved modulo 2

(blue ellipse) $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

(green box) $= (|\uparrow\circ\rangle + |\circ\uparrow\rangle)/\sqrt{2}$

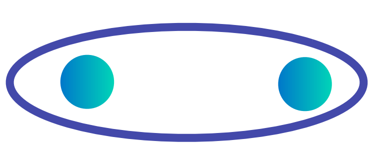
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

FL*

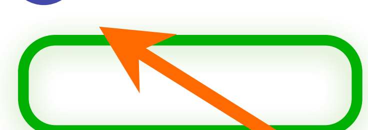


Place FL* on a torus:

obtain "topological" states nearly degenerate with quasiparticle states: number of dimers crossing red line is conserved modulo 2



$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$



$= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle \right) / \sqrt{2}$

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

FL*

We have described a metal with:

- A Fermi surface of electrons enclosing volume p, and not the Luttinger volume of $1+p$
- Additional low energy quantum states on a torus not associated with quasiparticle excitations *i*.e. emergent gauge fields

FL*

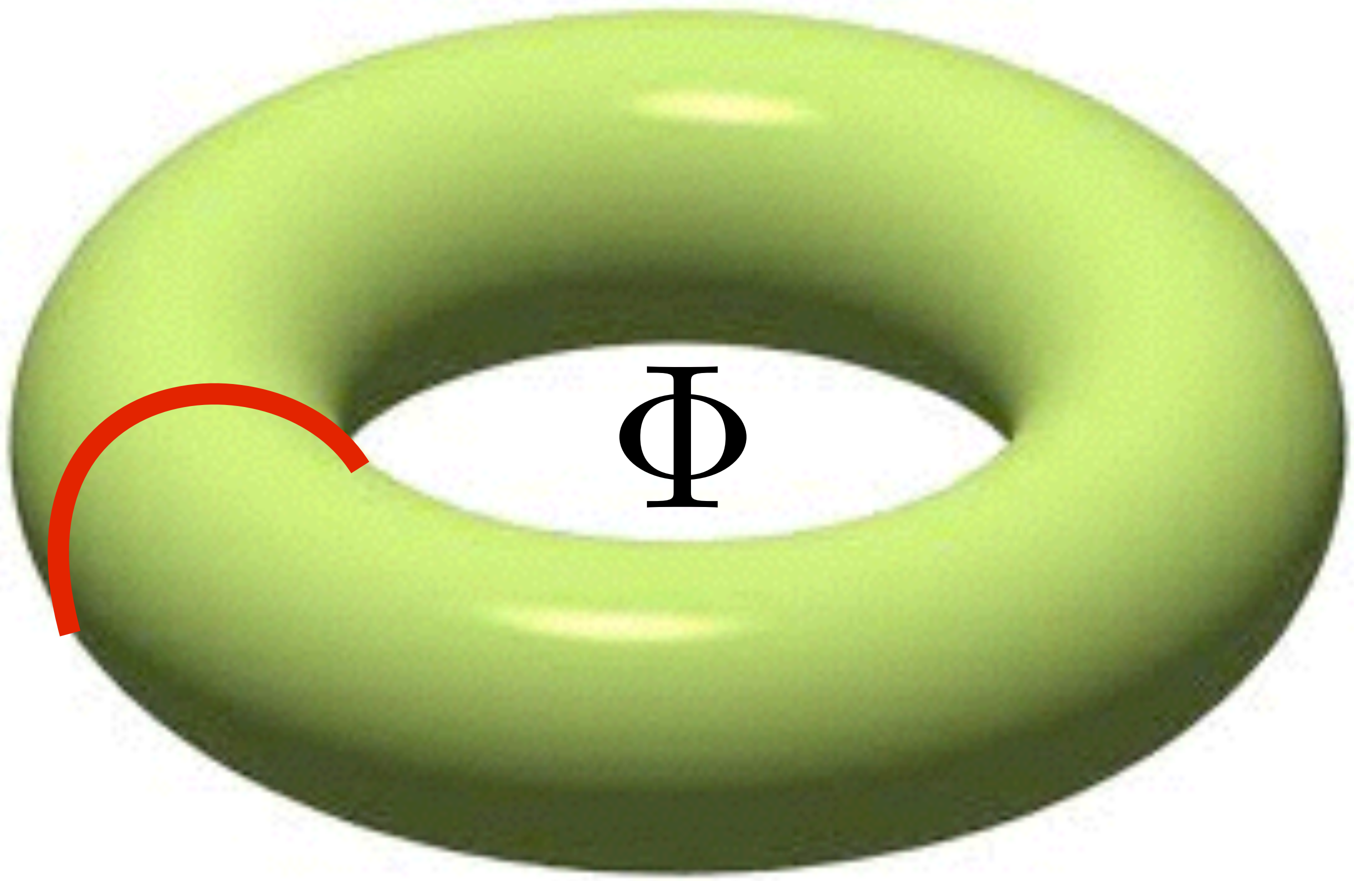
We have described a metal with:

- A Fermi surface of electrons enclosing volume p, and not the Luttinger volume of $1+p$
- Additional low energy quantum states on a torus not associated with quasiparticle excitations *i*.e. emergent gauge fields

There is a general and fundamental relationship between these two characteristics.

M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

FL*



Following the evolution of the quantum state under adiabatic insertion of a flux quantum leads to a non-perturbative argument for the volume enclosed by the Fermi surface

M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

1. Emergent gauge fields and long-range entanglement in insulators

2. Theory of ordinary metals: Fermi liquids (FL)

   (a) Quasiparticles

   (b) Luttinger theorem for volume enclosed by Fermi surface

3. The FL* phase:

   Quasiparticles with a non-Luttinger volume,
   and emergent gauge fields

1. Emergent gauge fields and long-range entanglement in insulators

2. Theory of ordinary metals: Fermi liquids (FL)

   (a) Quasiparticles

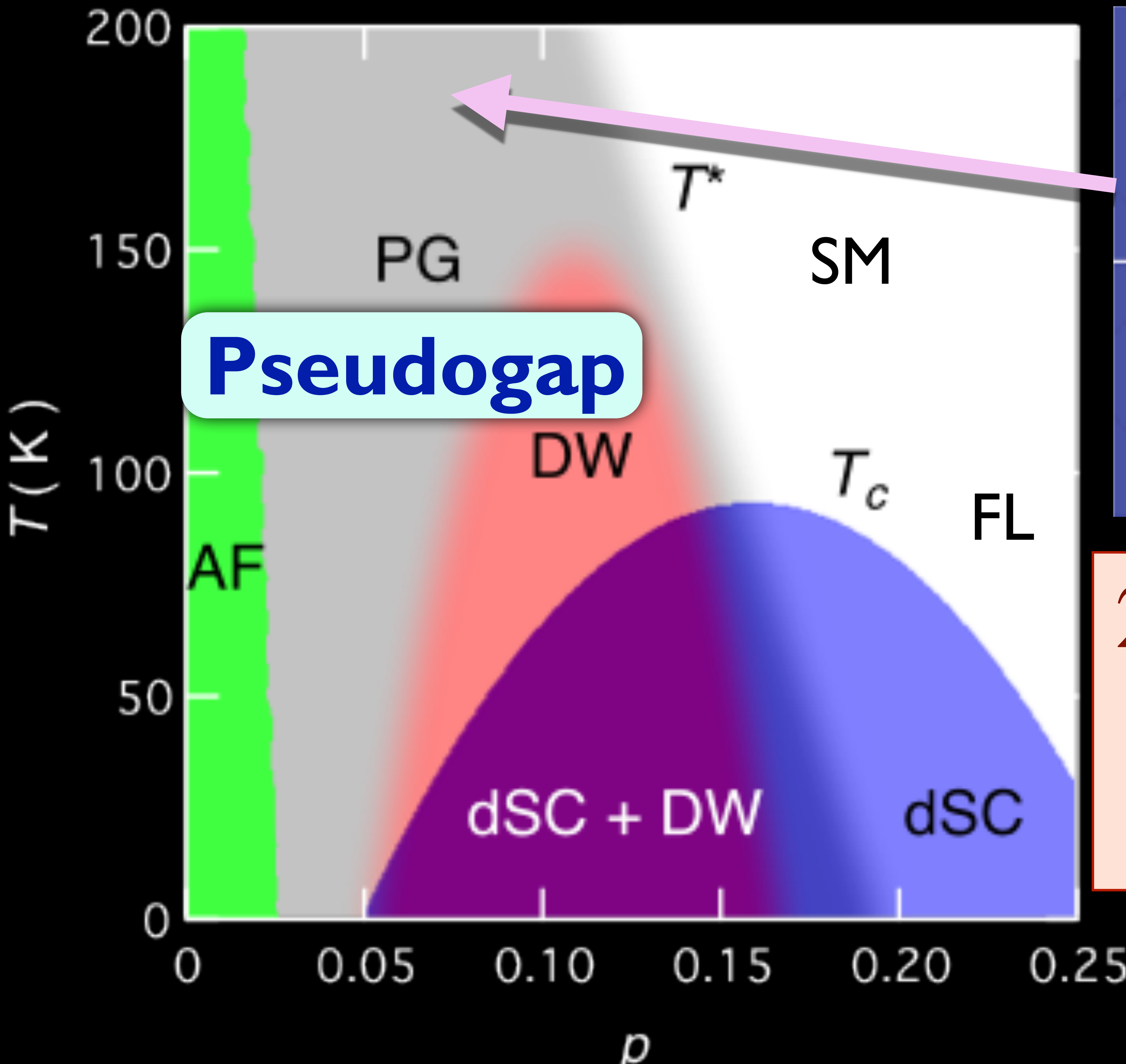
   (b) Luttinger theorem for volume enclosed by Fermi surface

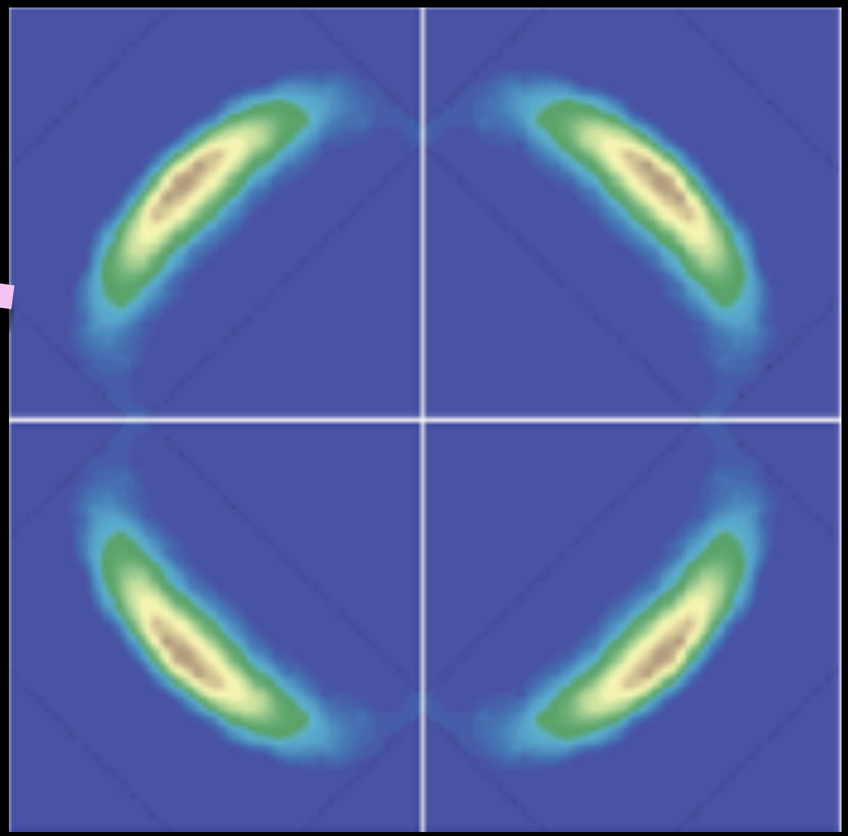
3. The FL* phase:

   Quasiparticles with a non-Luttinger volume, and emergent gauge fields

4. The pseudogap metal of the cuprate superconductors

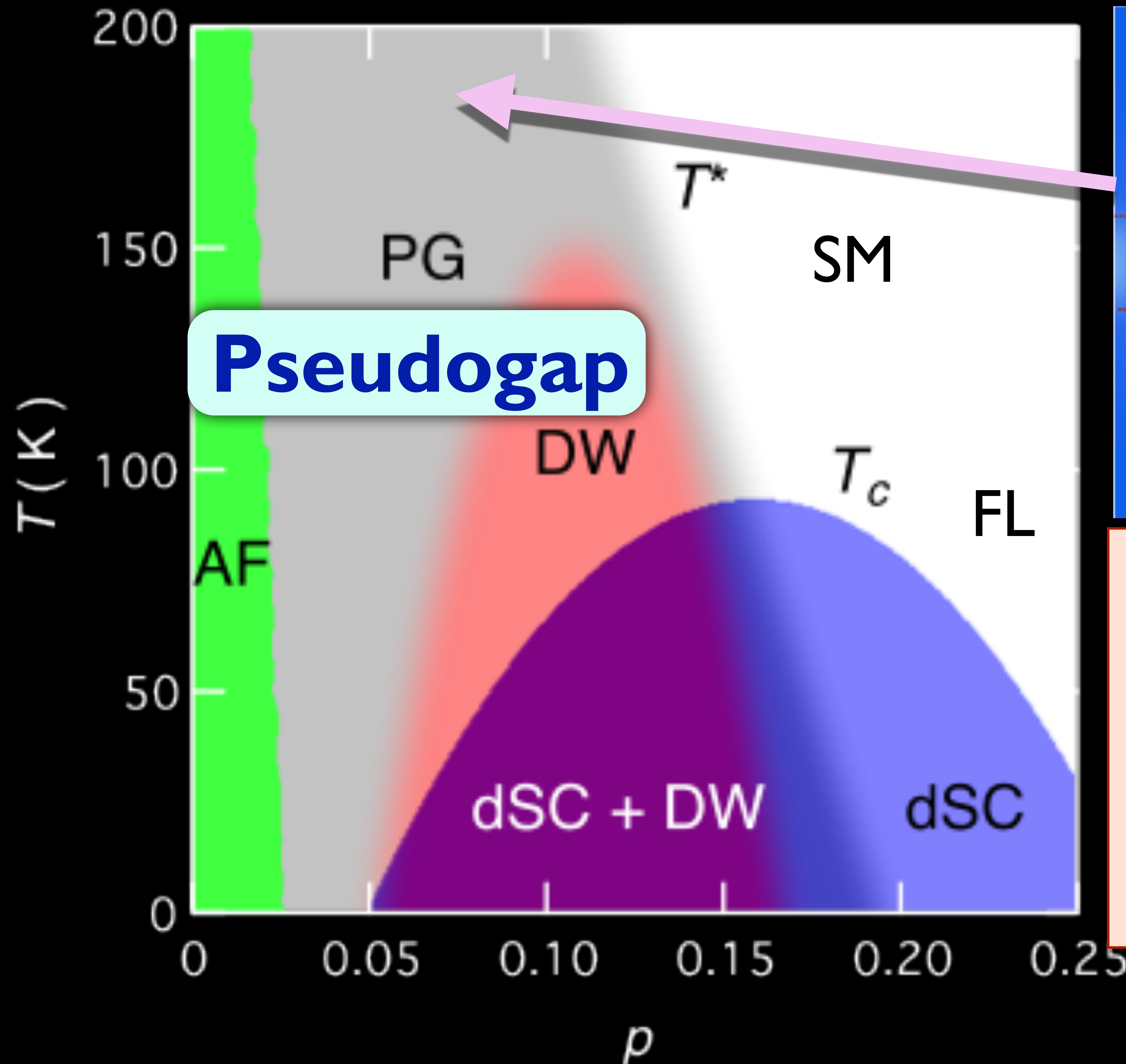
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

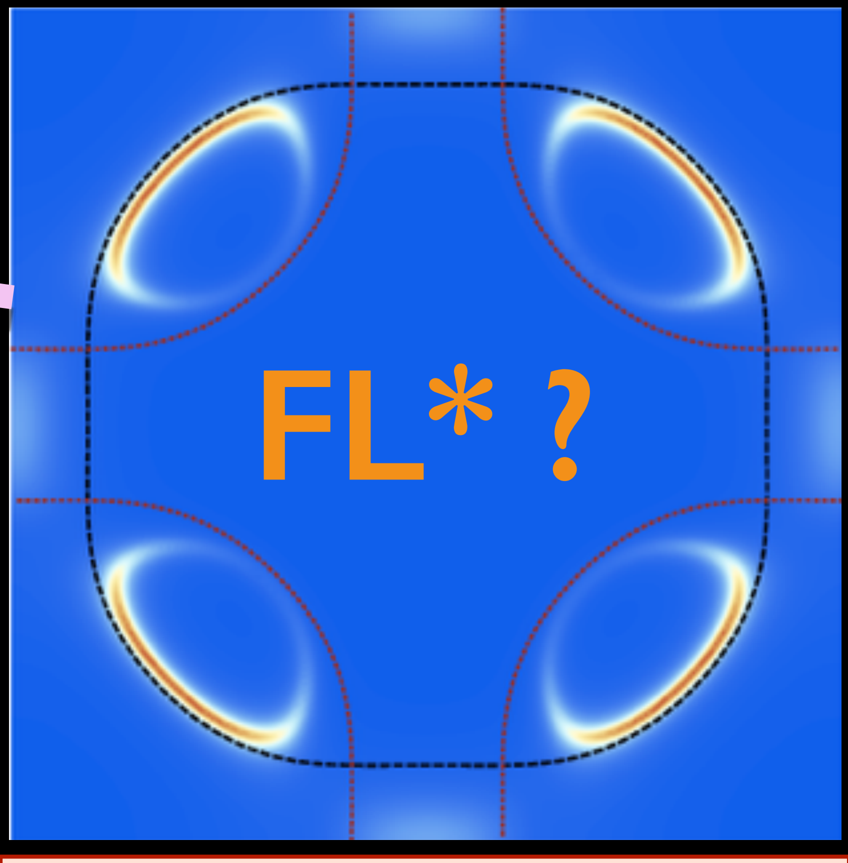




2. Pseudogap metal at low p

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)





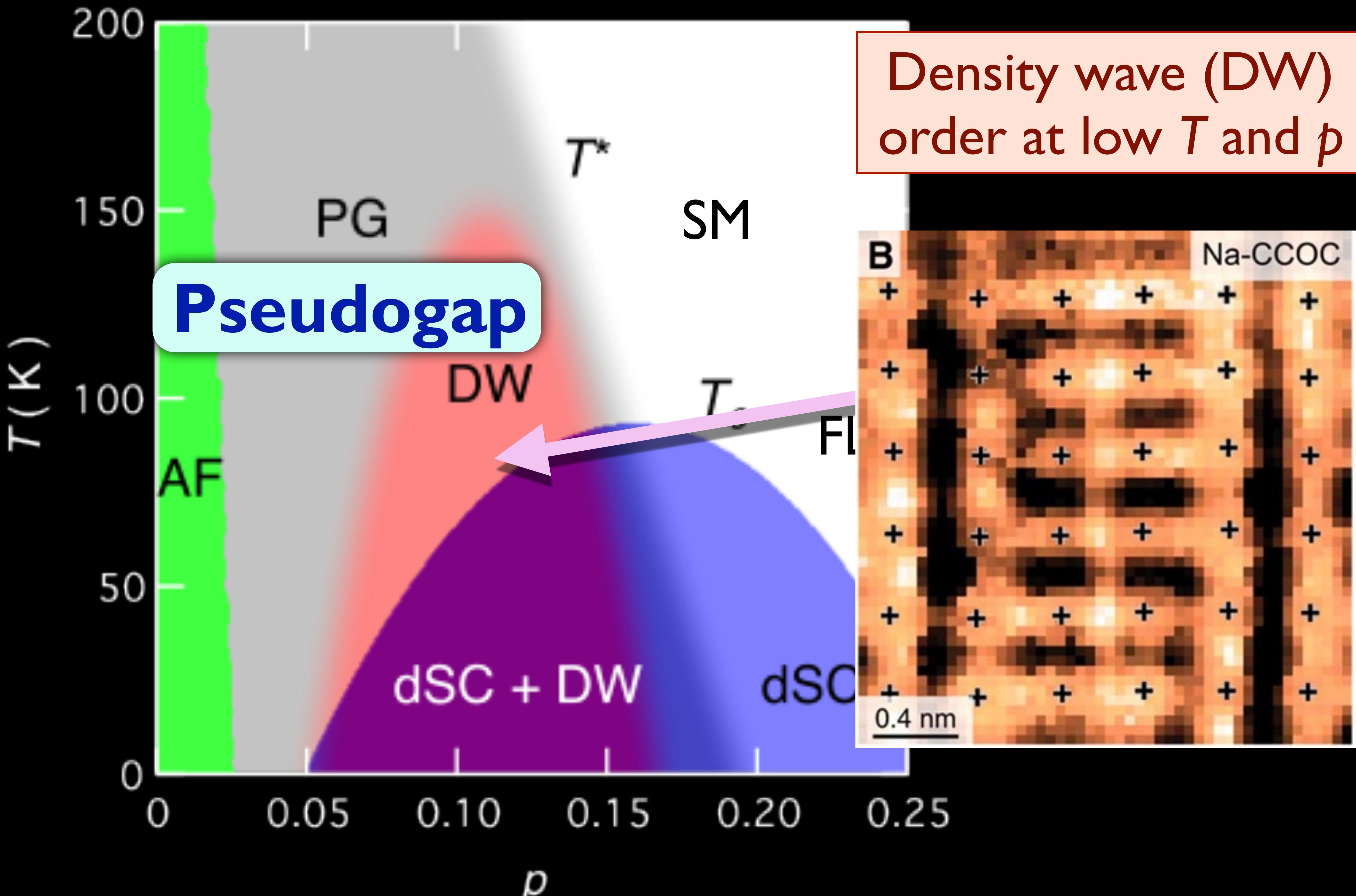
A new metal - FL*: with electron-like quasiparticles on a Fermi surface of size p <u>*and*</u> emergent gauge fields

Recent evidence for pseudogap metal as FL*

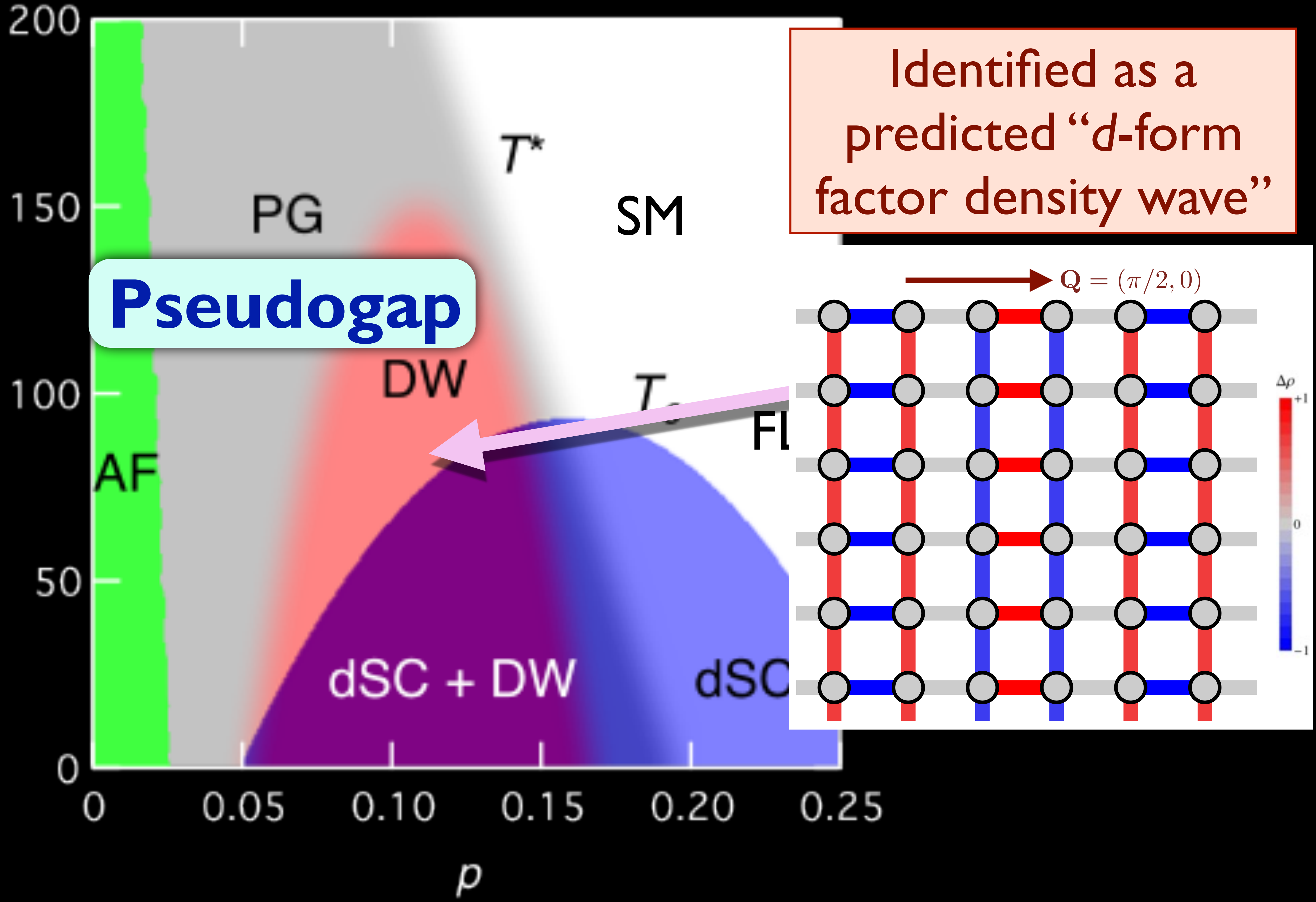
- Density wave instabilities of FL* have wave vector and form-factors which agree with STM/X-ray observations in DW region (D. Chowdhury and S. Sachdev, PRB **90**, 245136 (2014)).

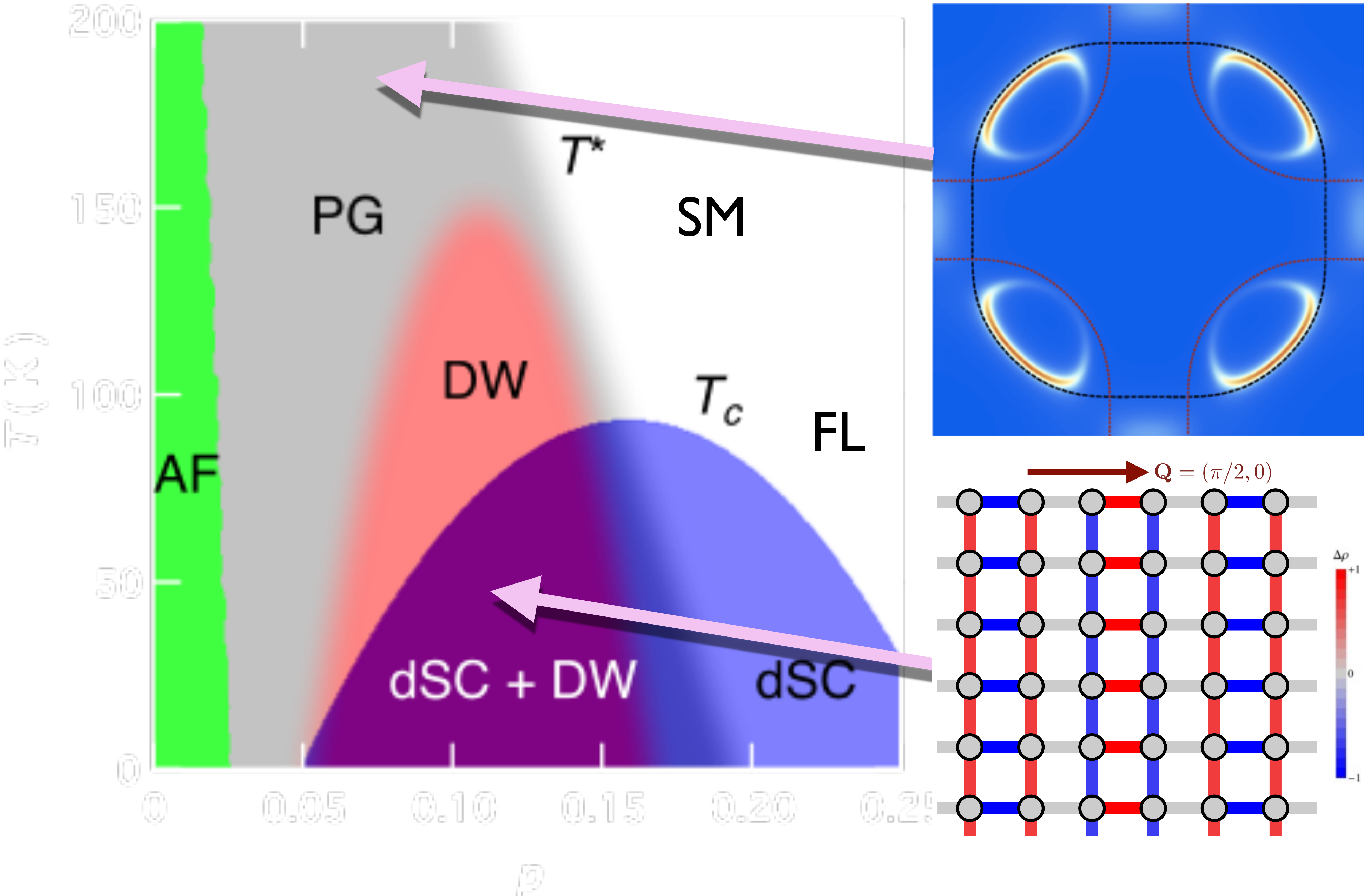
Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

Density wave (DW) order at low *T* and *p*

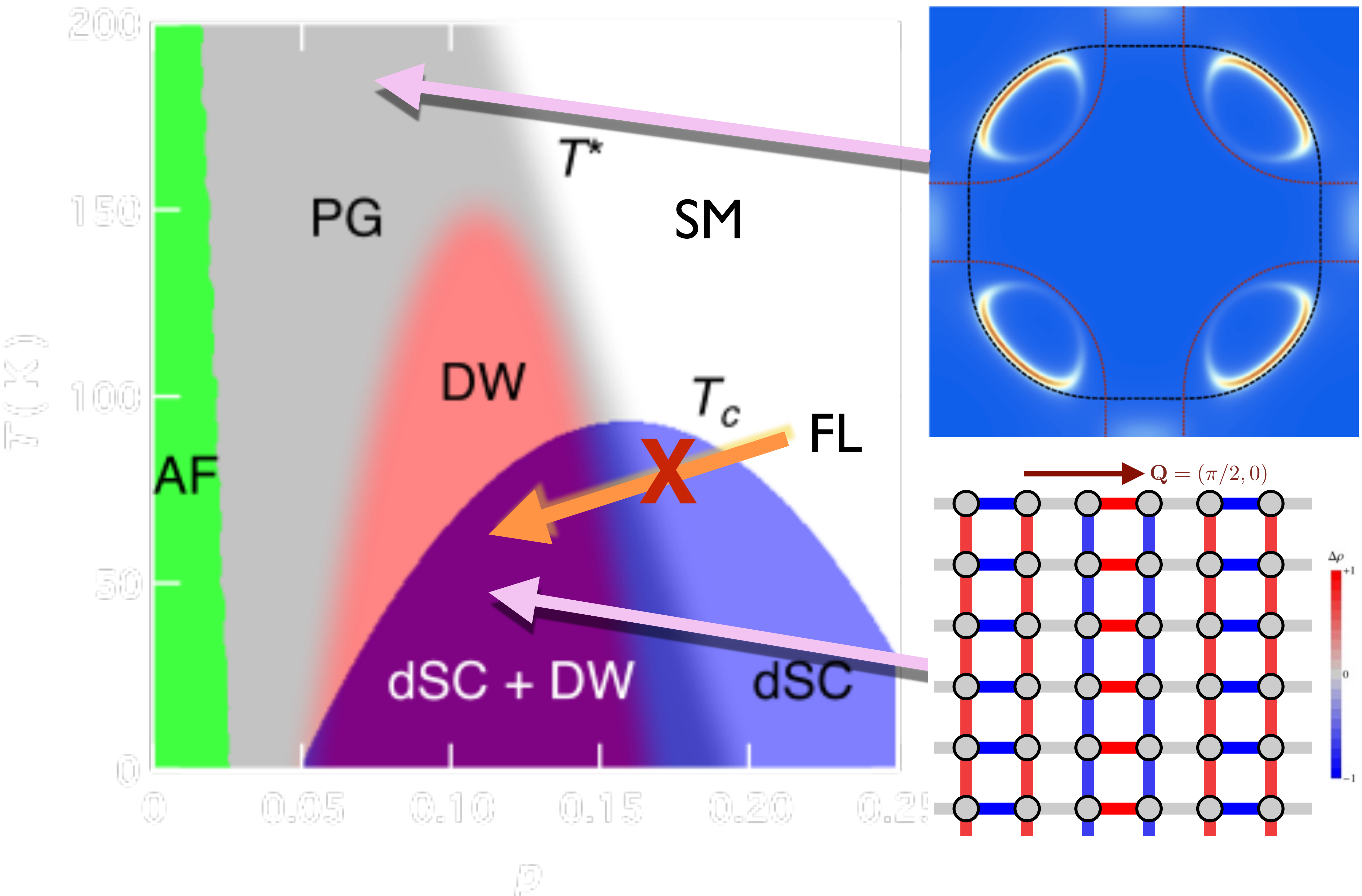


M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013). K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

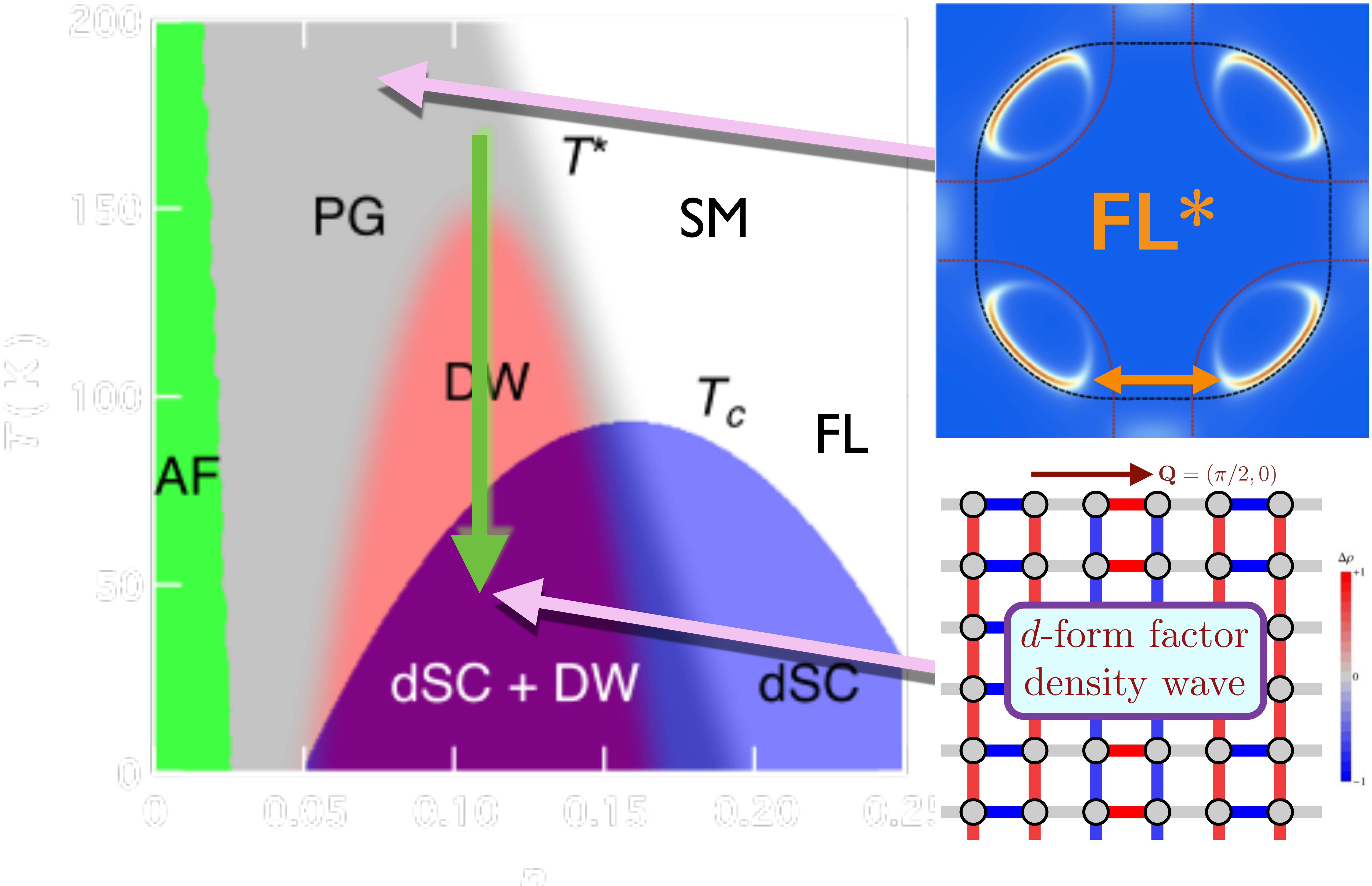




PG
SM
T^*
DW
T_c
FL
AF
dSC + DW
dSC
$\mathbf{Q} = (\pi/2, 0)$


200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
p
PG
SM
T*
DW
T_c
FL
AF
dSC + DW
dSC
X
Q = (π/2, 0)
Δρ
+1
0
−1

The high *T* FL* can help explain the "d-form factor density wave" observed at low *T*



D. Chowdhury and S.S., Phys. Rev. B **90**, 245136 (2014)

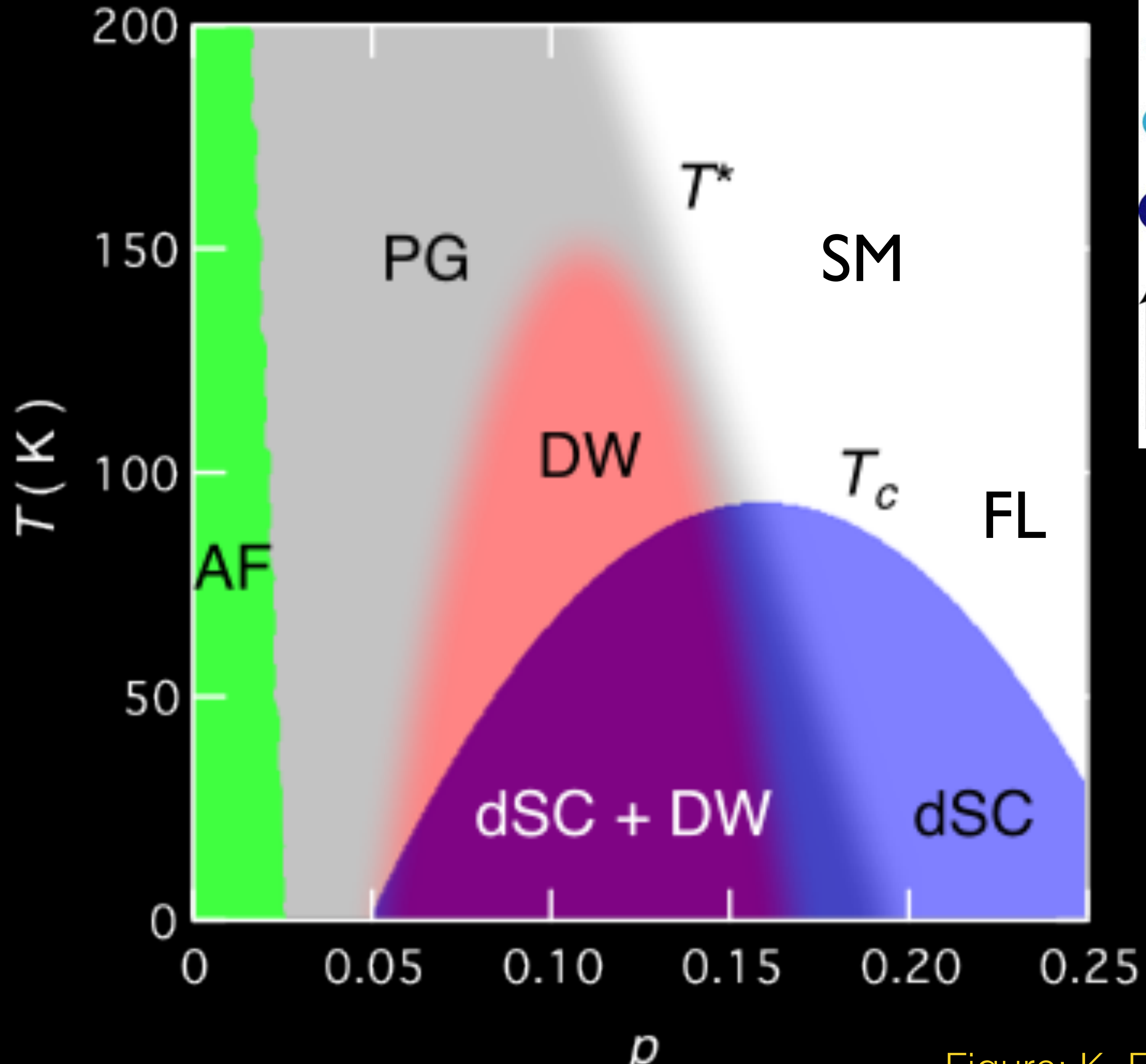
Recent evidence for pseudogap metal as FL*

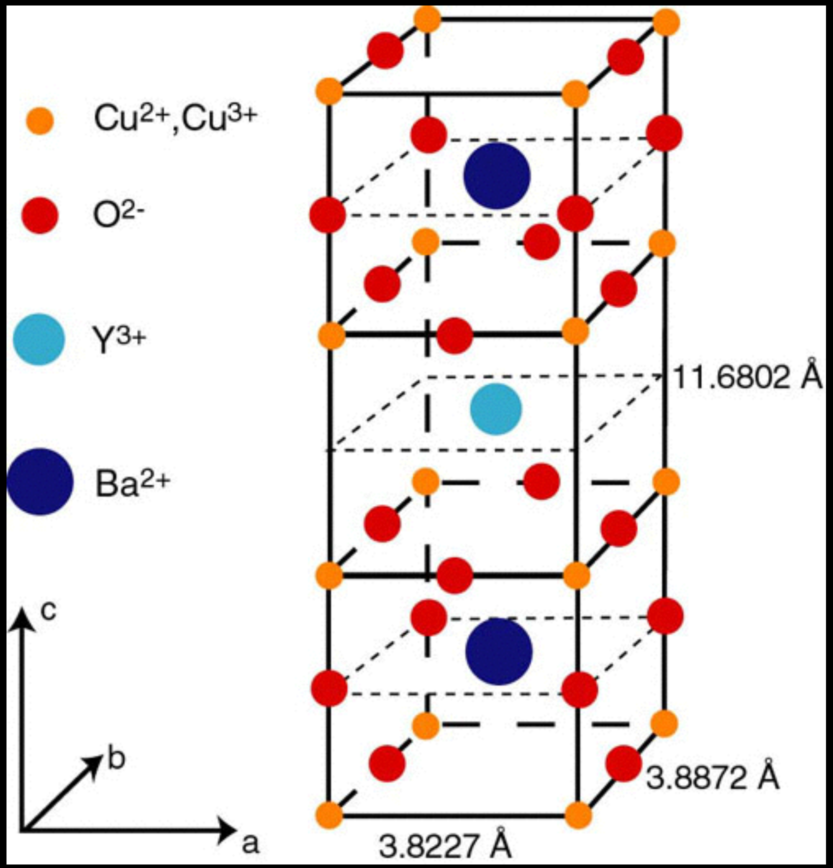
- Density wave instabilities of FL* have wave vector and form-factors which agree with STM/X-ray observations in DW region (D. Chowdhury and S. Sachdev, PRB **90**, 245136 (2014)).

Recent evidence for pseudogap metal as FL*

- Density wave instabilities of FL* have wave vector and form-factors which agree with STM/X-ray observations in DW region (D. Chowdhury and S. Sachdev, PRB **90**, 245136 (2014)).

- T-independent positive Hall co-efficient, R_H, corresponding to carrier density p in the higher temperature pseudogap (Ando *et al.*, PRL **92**, 197001 (2004)) *and* in recent measurements at high fields, low T, and around $p \approx 0.16$ in YBCO (Proust-Taillefer-UBC collaboration, Badoux *et al.*, arXiv:1511.08162).





$YBa_2Cu_3O_{6+x}$

Figure: K. Fujita and J. C. Seamus Davis

High field, low T measurements show a positive Hall co-efficient corresponding to carriers of density $1 + p$

Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162

$Ba_2Cu_3O_{6+x}$

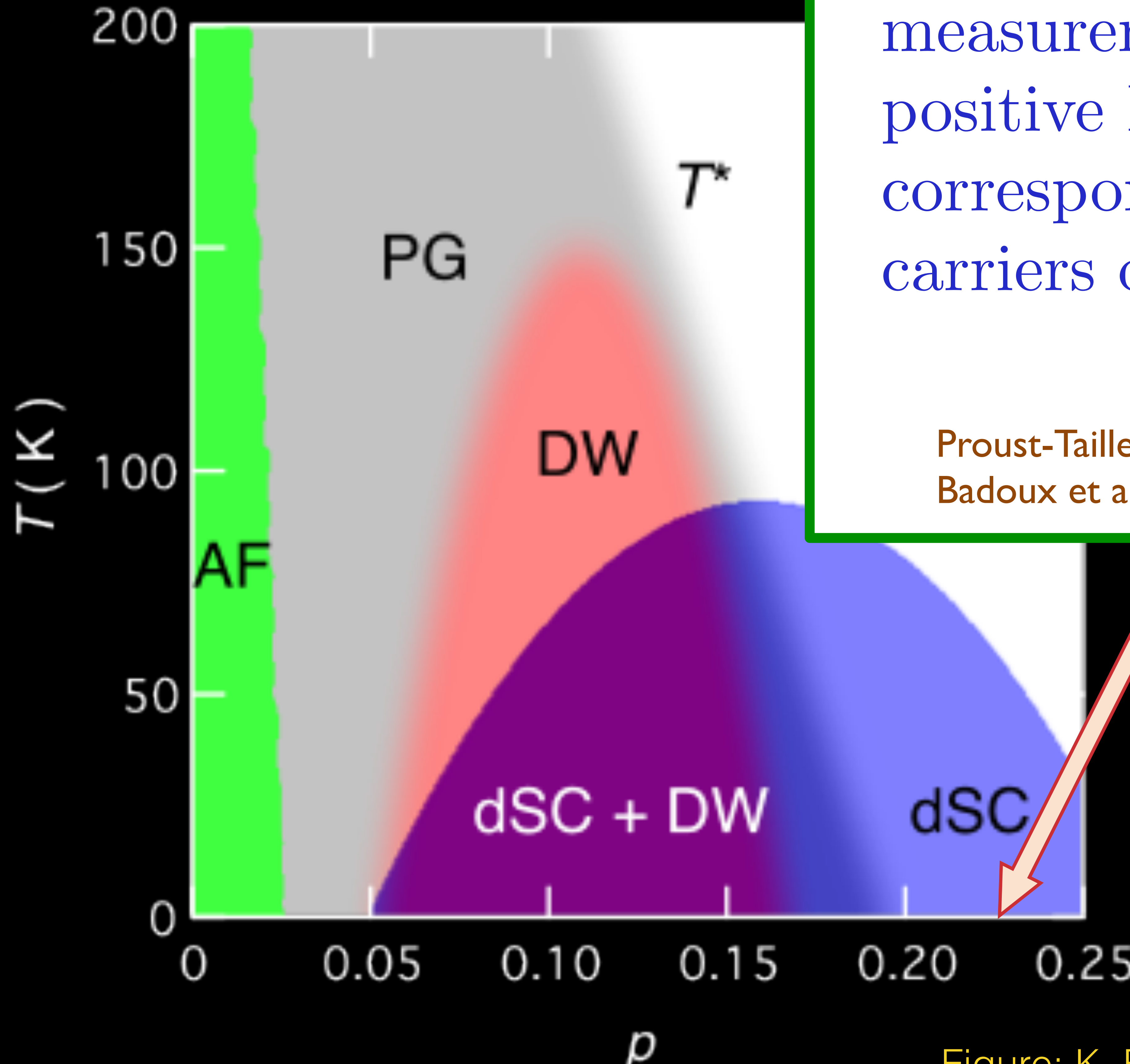
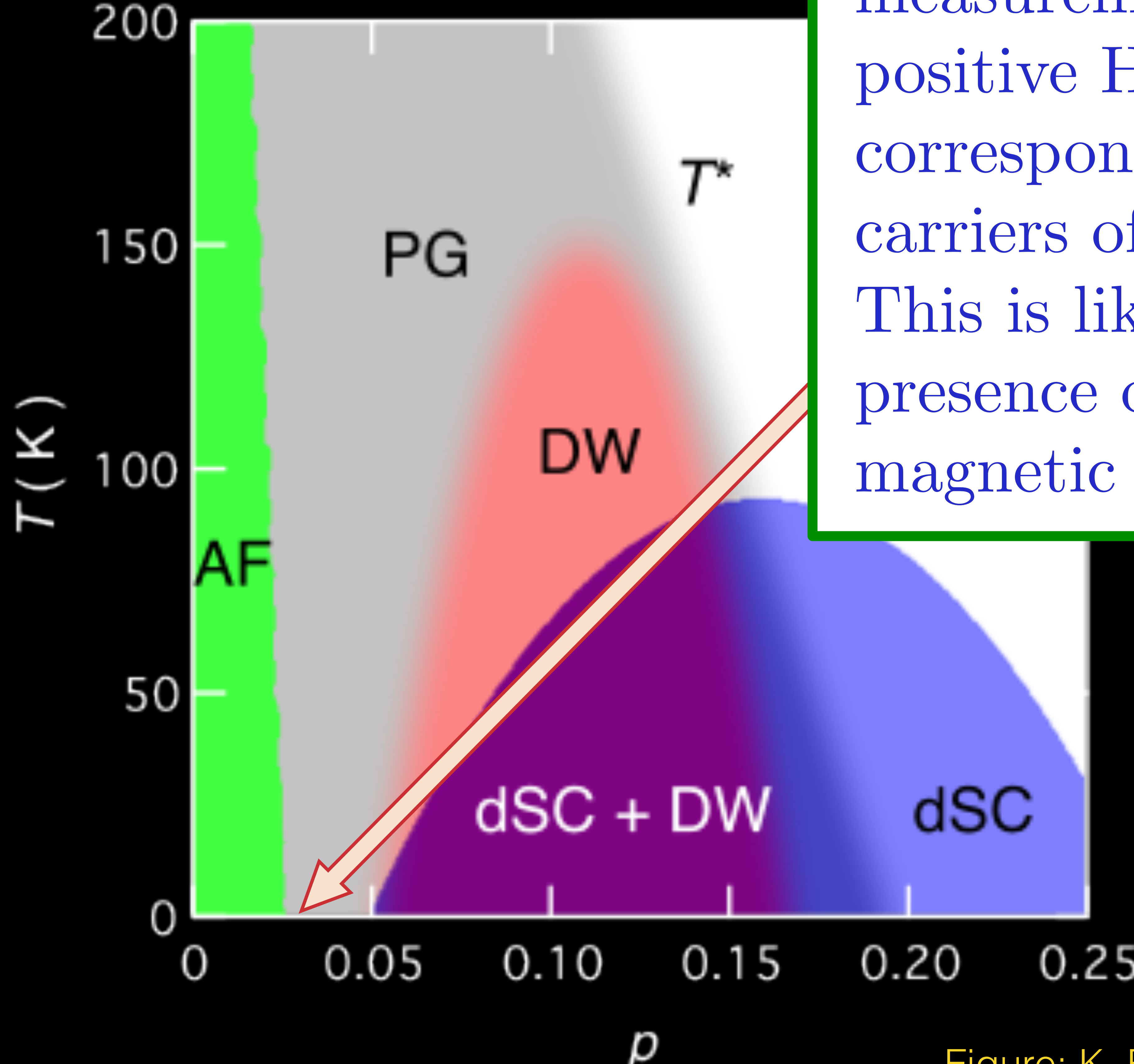


Figure: K. Fujita and J. C. Seamus Davis

High field, low T measurements show a positive Hall co-efficient corresponding to carriers of density p. This is likely due to the presence of antiferro-magnetic order.



$YBa_2Cu_3O_{6+x}$

Figure: K. Fujita and J. C. Seamus Davis

High field, low T measurements show a positive Hall co-efficient corresponding to carriers of density p

Proust-Taillefer-UBC collaboration,
Badoux et al. arXiv:1511.08162

$YBa_2Cu_3O_{6+x}$

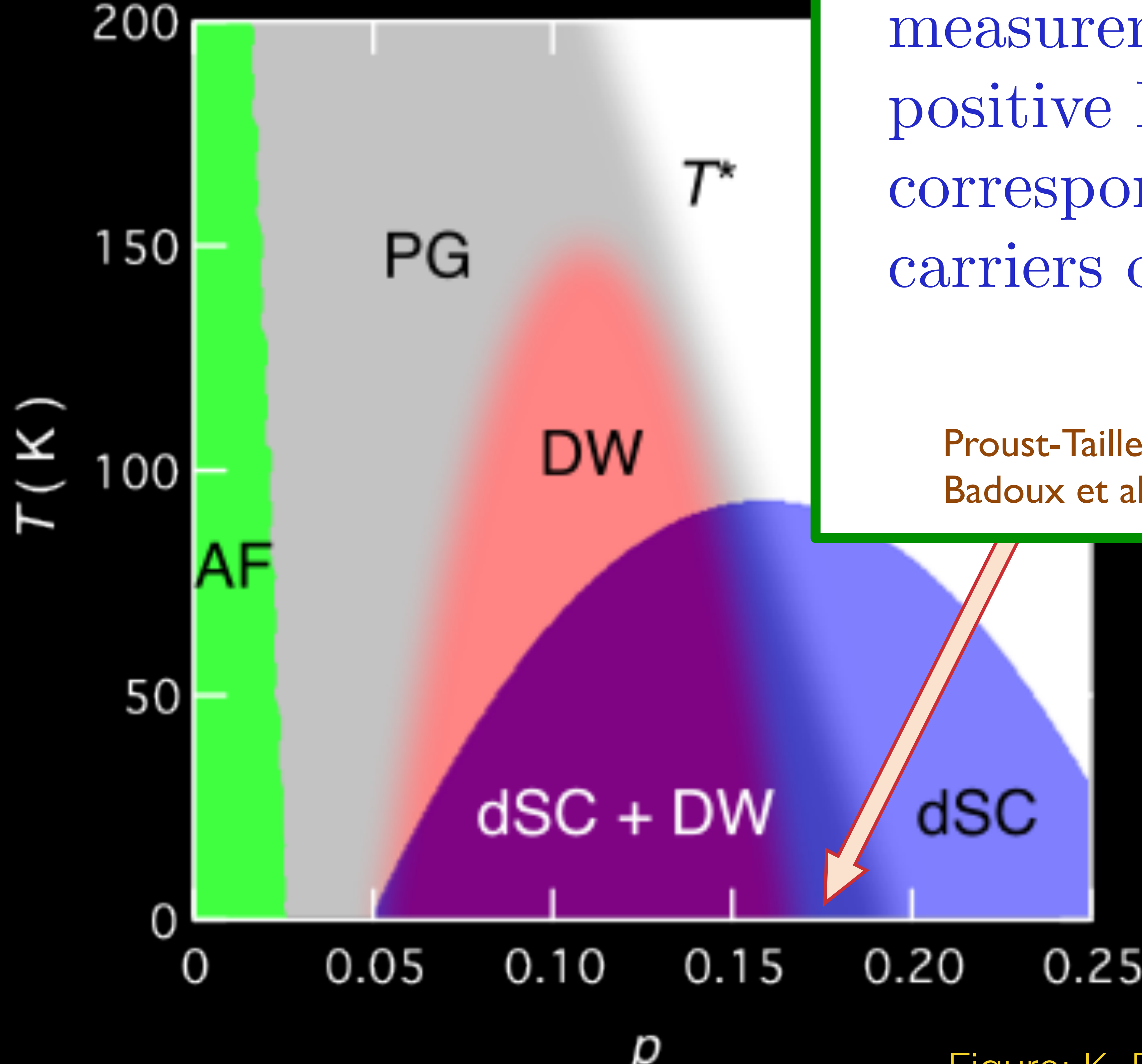
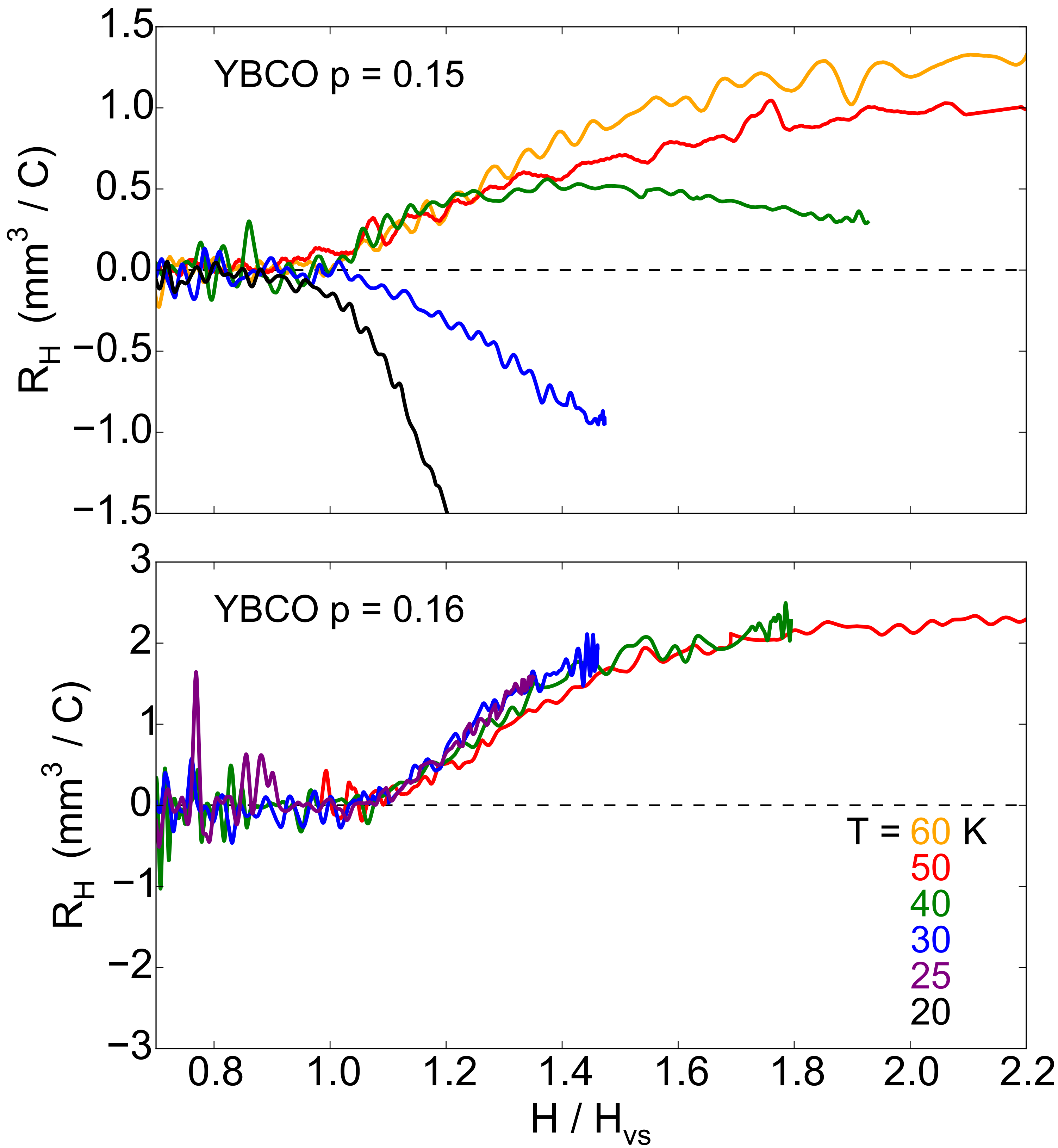


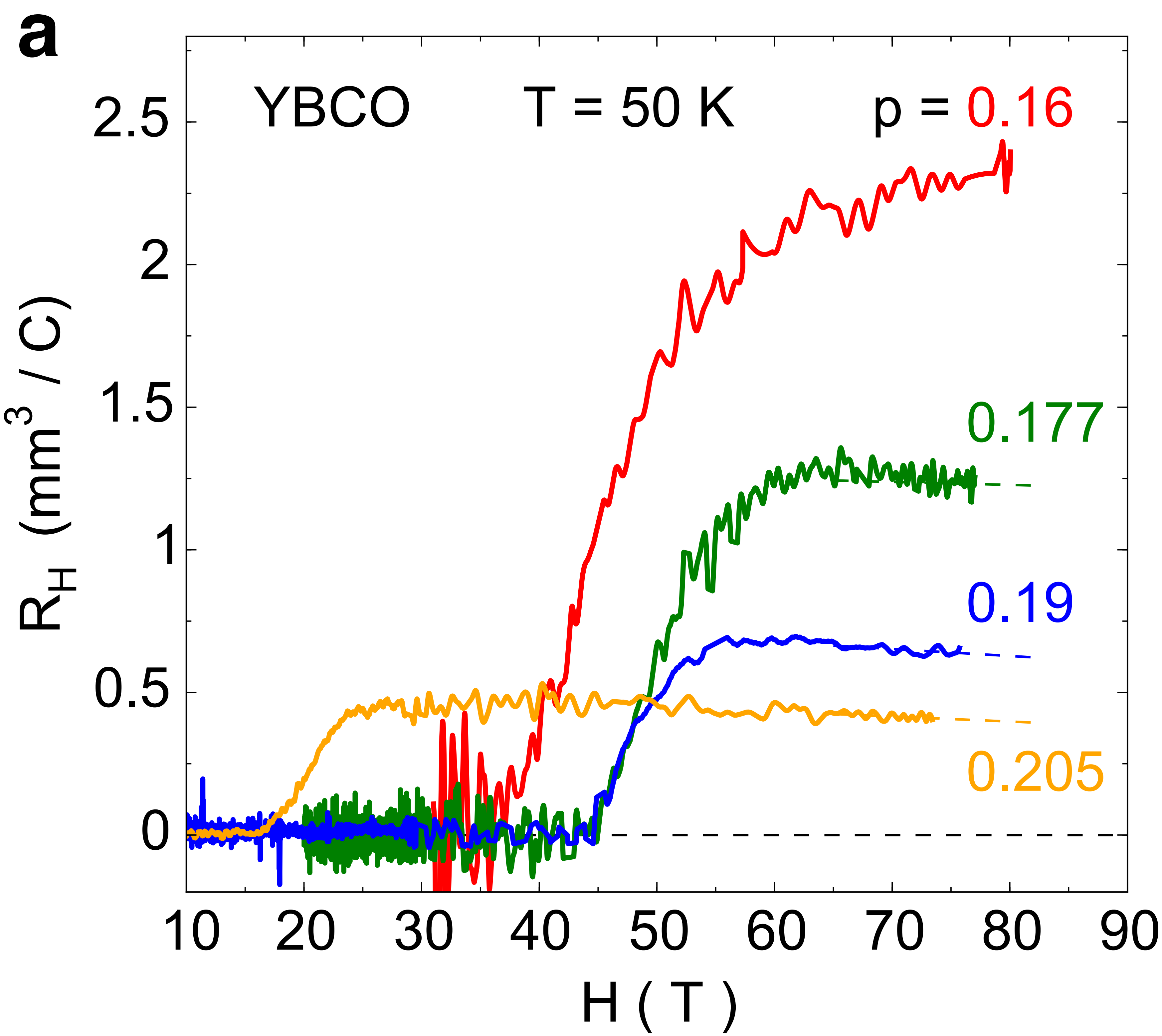
Figure: K. Fujita and J. C. Seamus Davis

Recent evidence for pseudogap metal as FL*



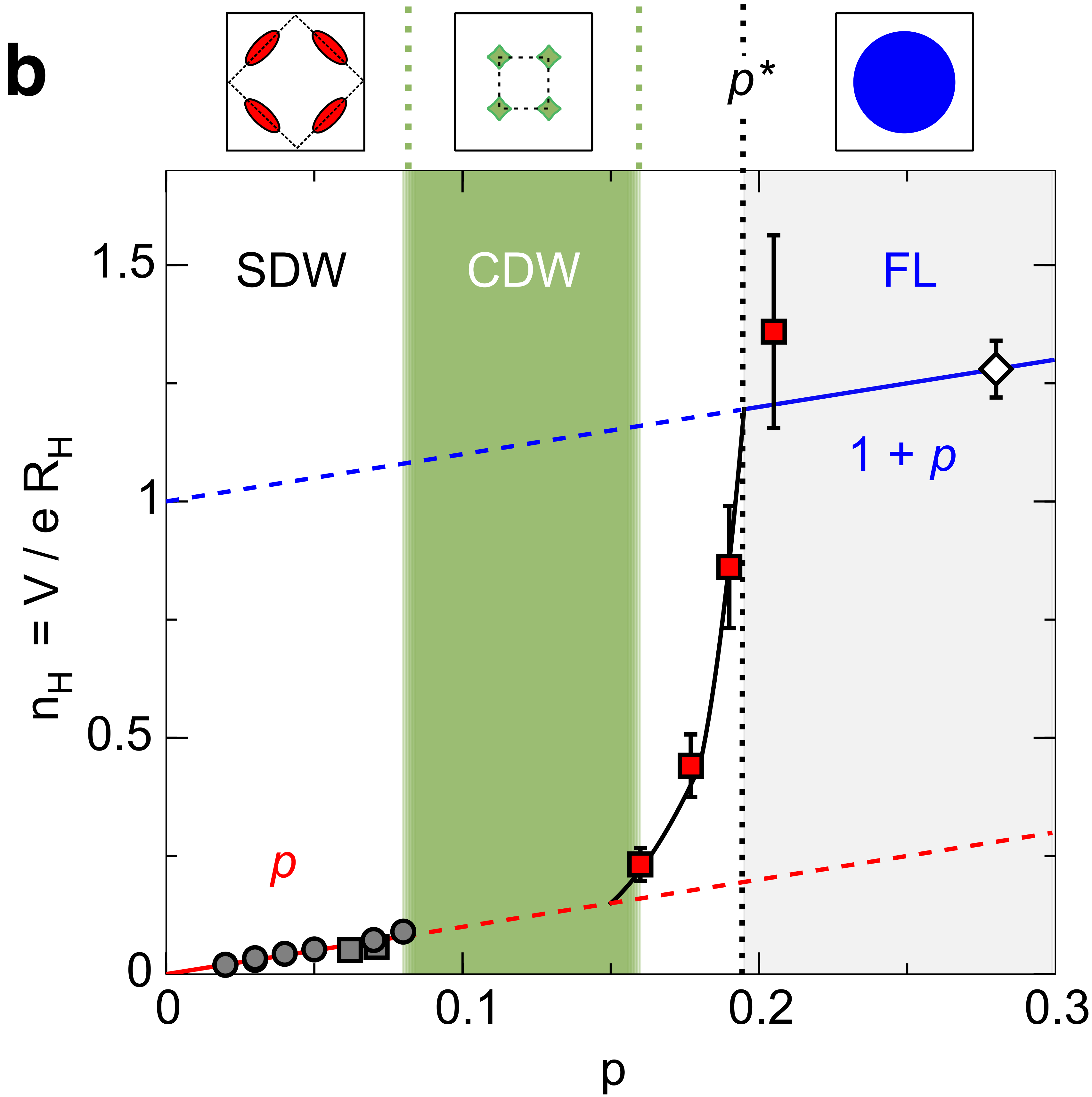
Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162

Recent evidence for pseudogap metal as FL*



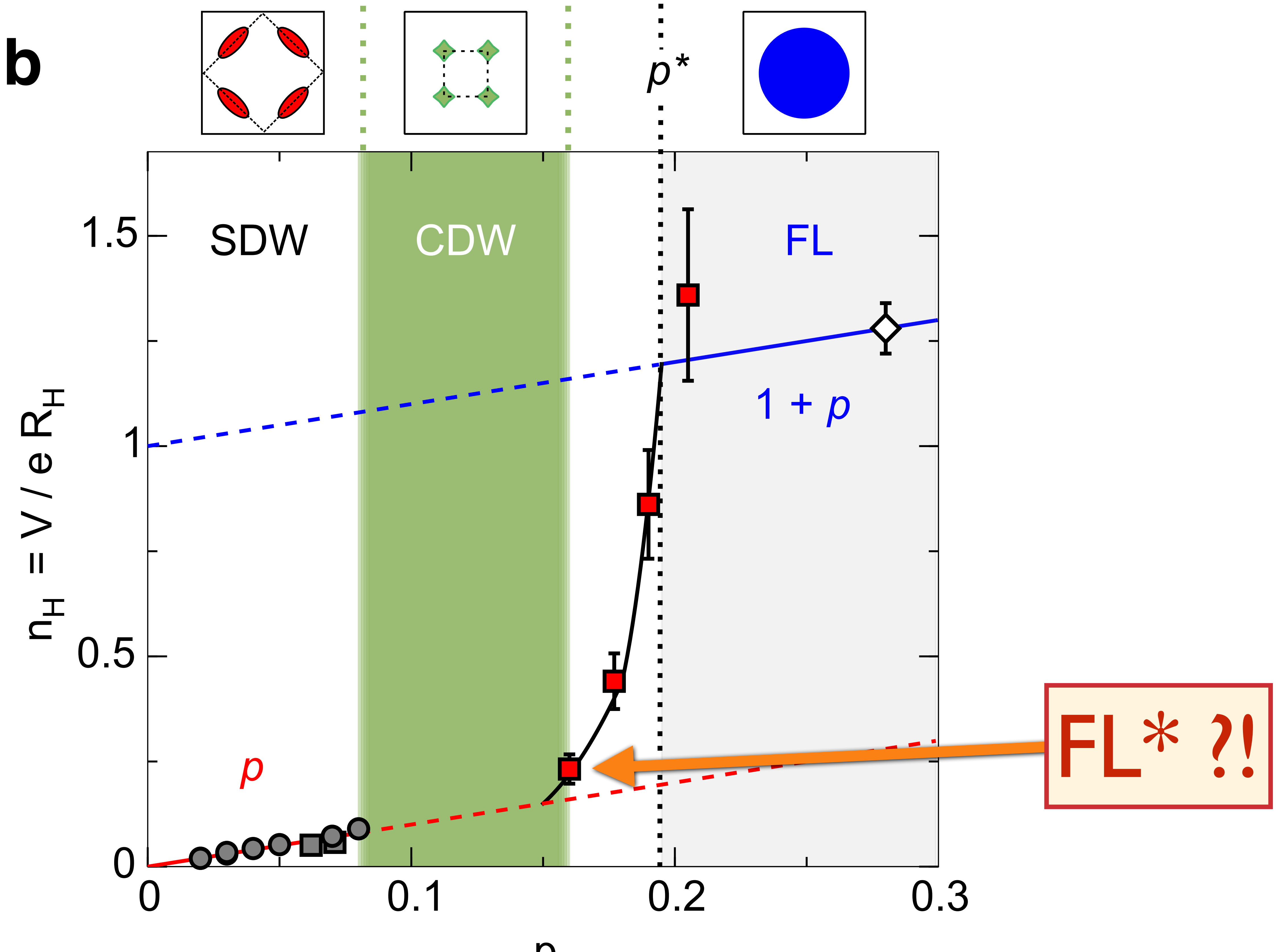
Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162

Recent evidence for pseudogap metal as FL*



Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162

Recent evidence for pseudogap metal as FL*



Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162

FL*

We have described a metal with:

- A Fermi surface of electrons enclosing volume p, and not the Luttinger volume of $1+p$
- Additional low energy quantum states on a torus not associated with quasiparticle excitations *i.e.* emergent gauge fields

FL*

We have described a metal with:

- A Fermi surface of electrons enclosing volume p, and not the Luttinger volume of $1+p$
- Additional low energy quantum states on a torus not associated with quasiparticle excitations *i*.e. emergent gauge fields

There is a general and fundamental relationship between these two characteristics. Promising indications that such a metal describes the pseudogap of the cuprate supercondutors